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ליד אוניברסיטת תל אביב

RADIO WAVE PROPAGATION IN THE IONOSPHERE

(A Comprehensive Review of Ongoing Research in Russia)

Interdisciplinary Center for Technological Analysis and Forecasting AT TEL-AVIV UNIVERSITY

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Russia has accumulated an enormous body of scientific information relevant to the global arms race. The subsequent commitment to the process of conversion has permitted a huge proportion of these technologies to surface in a manner permitting comparison and study. The result has been an exposure to enormous intellectual wealth, confronting us with the problem of studying, cataloging and applying it. This report summarizes the authors' visit to 17 major research institutions involved in ionospheric studies and identifies major achievements.

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(A Comprehensive Review of Ongoing Research in Russia)

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DECEMBER 1992

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CONTENTS

EXECUTIVE SUMMARY

We are living through a unique period in the history of science and technology. It is as if a huge pulse of scientific information is impacting the system and the system's reaction has yet to be determined.

Russia has accumulated an enormous body of scientific information relevant to the global arms race. The subsequent commitment to the process of conversion has permitted a huge proportion of these technologies to surface in a manner permitting comparison and study. The result has been an exposure to enormous intellectual wealth, confronting us with the problem of studying, cataloging and applying it.

The approach we have adopted in this study was based on two considerations: a) we decided to concentrate on the well-defined area, b) we wanted to do more than merely provide a list of individuals and institutes, but rather review and evaluate the relative capabilities of each research group and individual.

Using a variety of previous and fortuitous connections, we have succeded in creating a very congenial and supportive atmosphere in the institutes we have visited. In many cases, we have found people with an excellent knowledge base and capabilities who were, unfortunately, looking grimly towards what seems to be a bleak future. Perhaps this perspective has benefitted from our acknowledgement of their achievements and the spirit of cooperation encouraged by our visit.

Their willingness has been enhanced by the fact that one of us is a former colleague, and the other, an institute director (satisfying their traditional need for credibility). Although the Russians are extremely status conscious, we found them to be warm and mostly open

as they shared with us their profound concern for their country's future.

During our trip to Russia, we visited 17 major research institutions involved in ionospheric studies and received a general impression that the research is of very high quality.

We wish to identify two major achievements. First, an effective mathematical apparatus has been developed to describe wave propagation and diffraction in a variety of media. This apparatus makes it possible to calculate and optimize radio communication as well as to explain the physical nature of ionopsheric and magnetospheric processes.

Professor Babich and his co-workers at LOMI, St. Petersburg, are the leaders in the field of mathematical methods. Professor Erokhin at IKI, Moscow, is very prominent in the field of nonlinear interaction of wave beams with particles. Professor Mishin at IZMIRAN, Moscow, has achieved major advances in solving problems of fine structure of the auroral ionosphere and in forecasting of radiochannel in a disturbed ionosphere. Professor Cherkashin and Dr. Popov at IZMIRAN, Moscow, have developed great expertise in calculating radio signal features propagating through the ionosphere.

The second area of excellence is the research in heating the ionoshere by high power radio waves. The major achievements in this field are those of Professor Erukhimov and his colleagues at NIRFI, N. Novgorod, as well as of Academician Gurevich at FIAN, Moscow, and Professor Rapoport and Drs. Benedictov and Mityakov at NIRFI, N. Novgorod.

We would also like to mention Professor Troshichev from AANII in St. Petersburg, for his studies on the magnetosphere and the polar ionosphere and Professor Lukin from MFTI in Moscow for his calculations of wave catastrophy functions.

We should emphasize the following, concerning the financing, infrastructure and scientific equipment of research institutions we have visited. Most institutions were strongly supported, until recently, by the military. Now, with a large reduction in military financing, the Russian Academy of Sciences can support only one half of the required budget. This situation has greatly affected the infrastructure and the procurement of equipment in these institutions. Young investigators are leaving laboratories for more secure sources of income. Only those Heads of Deparments who are able to find alternative sources of support are managing to keep up the level of the research.

An example of this serious predicament is the St. Petersburg Branch of Steklov Mathematical Institute (LOMI) (see enclosed). The staff of this Institute had not been paid for four consecutive months. Similar situations occured at the Institute of Physics of the Atmosphere (IFAN) and Radio Research Institute (NIRFI). On the other hand, Space Research Institute (IKI), Institute of Terrestrial Magnetism, the Ionosphere and Radio Wave Propagation (IZMIRAN), Radio Research Institute (NII Radio), St. Petersburg Institute for Aviation Instrument Manufacture (LIAP) are managing to diversify, in part, away from military funding and their functioning is therefore relatively stable. In practically all the places that we visited there was a great interest in the possibility of obtaining foreign grants for proposed projects via this report.

Teaching institutions, unlike the research centers, are better subsidized mainly through the Ministry of Higher Education. The Moscow Institute of Physics and Technology (MFTI) (see enclosed) represents a unique case of a "russian" teaching institution. As such, it is exeptionally strong in training in basic sciences while the same time providing its graduates with a clear direction in applied projects through MFTI's strong links with leading Research Institutes both with the Academy and Military-Industrial Complex.

The following review consists of four chapters: Chapter 1 briefly describes the history of radiophysics in Russia, defines terminology and identifies the main directions of ionospheric research. Chapter 2 reviews the field of radio wave propagation in the ionosphere, describes the main achievements, analyses methodology and reflects upon probable future development of this field. Chapter 3 examines specific projects of ongoing research in Russia. Chapter 4 describes and analyses major Russian centers on ionospheric research, their structure and leading research groups. We conclude with the list of 19 institutions and their leading scientists.

CHAPTER 1:

INTRODUCTION

1.1 This report describes the current status of Russian research in the field of Radio Wave Propagation in the ionosphere and identifies the expertise and applications which could be useful for the US Airforce research community.

1.2 To define the scope of this review we shall first establish the basic concepts:

Radio waves are electromagnetic waves with the frequency below $3 \cdot 10^5$ MHz.

The ionosphere is the upper layer of the terrestrial atmosphere ($\sim$100-1000km) consisting mainly of a mixture of gases ionized by the ultraviolet X-rays and corpuscular radiation emanating mainly from the sun.

The ionosphere itself consists of several layers differing in the degree of their electron density. The interior structure of the ionosphere varies with time as a result of the level of solar and magnetic activity. It depends on the time of the day, season, latitude, longitude and other factors.

The conditions in the ionosphere (ion and electron density, temperature, magnetic and solar activity) strongly affect radiocommunication, especially its range, the absorption of radiowaves and noise level.

The operating diagnostics and prognosis of the parameters of the ionosphere allow the selection of the optimal characteristics of a radiosignal: its shape, frequency and power. Moreover, attempts are made to induce man-made changes in the ionosphere to test radio wave propagation.

1.3 Traditionally, Soviet science has been very strong in the field of radiophysics, both in theory and in application. In the early twenties, by Lenin's decree, the first radio science center was established in Nizhny Novgorod (formerly Gorky). It served as the basis for the subsequent development of research centers in Moscow, Leningrad and Siberia. The vast size of the Soviet Union required the development of an efficient communication system. Thus, it was necessary to stimulate radiophysics research. In addition, the development of the industrial military complex also required strong radiophysics research and respective technology. Today, more than 40 research centers (see map, page 8) are involved in basic and applied radiophysics.

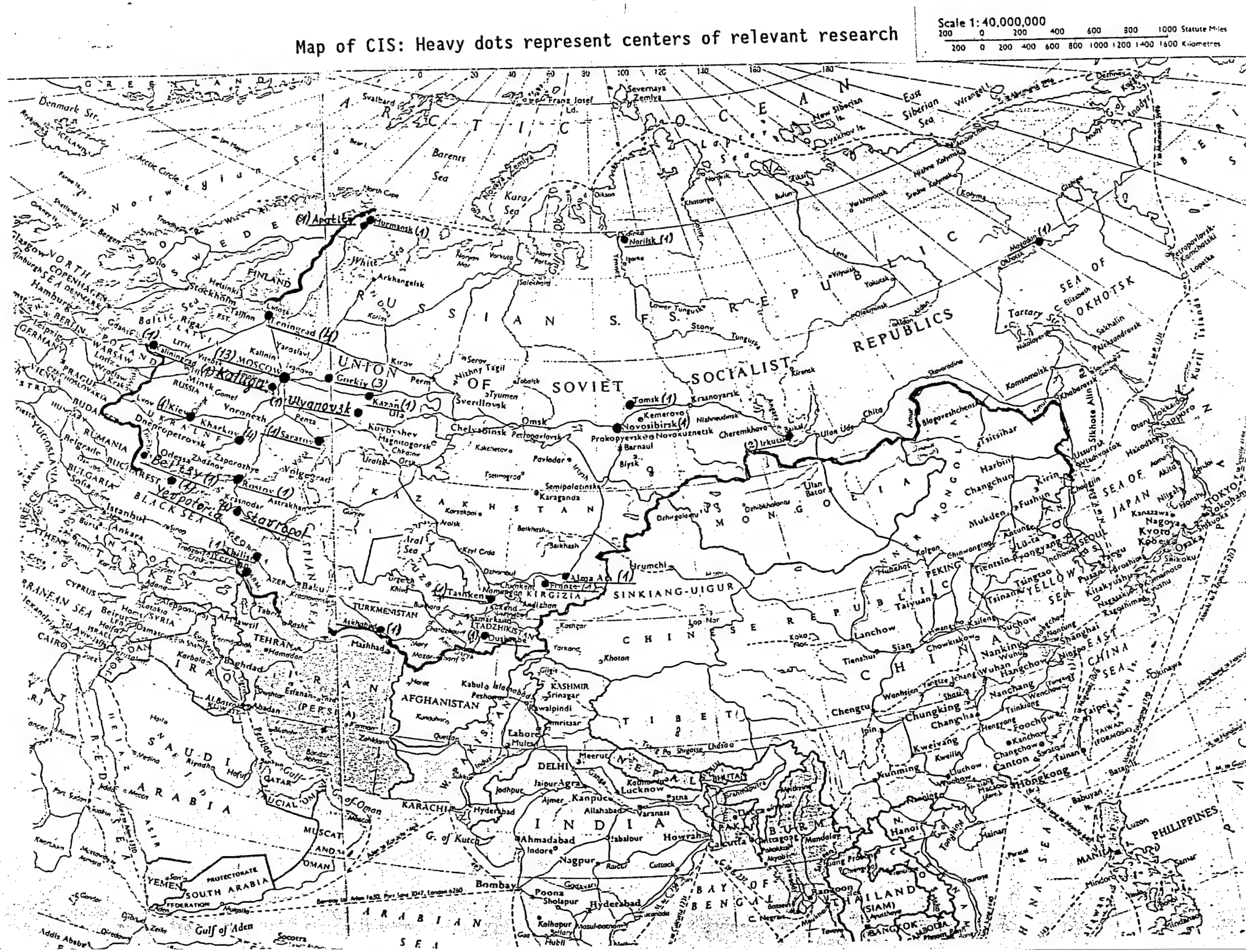
The investigation of the ionosphere has been developed in four directions:

a) ionosphere data processing,
b) theoretical treatment of wave propagation in the ionosphere,
c) ionosphere modelling.
d) ionospheric heating.

a) Ionosphere data processing includes the processing of the experimental ionosphere data received from the vertical and oblique sounding of the ionosphere for the diagnosis of the ionosphere and the forecasting of its behaviour. The achievements in this field are closely connected with a progress in measurement techniques.
The appearance of digital ionosondes recently opened new perspectives for obtaining additional information about the ionosphere. The use of digital ionosondes for ionosphere research and developing new methods of the ionosphere data processing make possible the real time diagnostics of the ionosphere parameters.

b) The second direction involves the development of theoretical methods to solve the problems of radio wave propagation in inhomogeneous dispersive ionospheric plasma including ionospheric irregularities [1-7].

Map of CIS: Heavy dots represent centers of relevant research



Different approaches for the description of wave propagation and scattering in deterministic and random media have been developed.

The theory of perturbation, physical optics approach or other variational methods are used for description intensity and phase fluctuations, beam propagation, coherence and backscattering enhancement when solving the problems of radio wave propagation in random ionosphere [3,4,7].
Geometrical optics methods with the help of space-time rays are widely used for determination parameters and trajectories of propagating signals [3-5]. The use of parabolic equation method, Gaussian beam method and some others asymptotic expansion methods make it possible to solve the nonstationary problems of radio wave propagation. Some of these methods make it possible to determine wave field structure and dispersion distortions of radio signals in the field of caustics and space-time focuses [6,7].
The numerical methods for solving wave equations treat the problem of radio wave propagation when it is impossible to obtain an analytical solution.

c) Ionosphere modelling, the third direction of ionospheric research, is the theoretical and experimental modelling of the ionosphere and includes the design of the ionospheric global models. The behavior of the ionosphere, and especially that of the F-region, is very complicated because of the dependence of the ionospheric parameters on many factors, as mentioned above. It is still impossible to describe all ionospheric features and anomalies by the unique global model. Therefore, many regional models for representing electron density, collision frequency, ions velocity and other parameters in different ionospheric layers in the middle ionosphere, low latitude ionosphere and auroral ionosphere have been developed.

There are two approaches to the creation of ionospheric models. The empirical models are created by using the experimental data obtained from results of vertical and incidence sounding of the ionosphere by ionospheric stations and satellites.The difficulty is to solve inverse problems - to draw up the ionospheric behaviour pattern from the experimental data. The theoretical models are created by means of numerical solving a complete set of equations. Semiempirical models include both an empirical and theoretical part. Moreover, the data of the empirical part are used for correction of the theoretical part of the model.

d) In the last few years a new perspective direction of ionospheric research has been developed. It has been connected with effects of high power radio waves on the ionosphere. The heating of the ionosphere by intense radio waves induces artificial plasma turbulence which changes the behaviour of the heated ionospheric region. The theoretical understanding of this phenomena is controversial.

These experiments of heating the ionosphere by high-power radio waves are conducted to investigate an artificial plasma turbulence with the intention of managing it.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The ionosphere, a plasma surrounding the earth, plays an important role in the propagation of radio waves (from very short waves right up to wavelengths of tens kilometers or more). Furthermore, the investigation of the ionosphere itself has largely been carried out by radiophysical methods. Therefore, the exposition of the various ionospheric phenomena cannot be separated either from the radio measurements or from their theoretical analysis (i.e., from radio wave propagation in the ionosphere).

We present here an overview of the basic directions of Russian research in the field of radio wave propagation in the ionosphere. We also try to include and elucidate present achievements, consider the physical origins of the main difficulties and limitations for the problems to be solved and speculate about further research and development in this field.

2.2 Historical and scientific background

The ionospere is a very specific part of the earth's atmosphere. The first direct experiments by Appleton, and also by Bright and Tuve, which established the existence of the ionosphere, date back to 1925, when the reflection of radio waves was observed from the regions of the atmosphere at an altitude of approximately 100 km above the earth's surface.
These observations indicated that reflections are also produced at altitudes of 200 km and above. Further fixed-frequency investigations have shown the splitting of the incident wave into an "ordinary" and an "extraordinary" wave in the earth's magnetic field. Experiments indicated that the signal delay

changed with varying the frequency of the radiated waves. These observations led to the conclusion that the electrons, rather than ions, are the principal agent participating in the propagation of radio waves through the ionosphere. If these were ions, it would be difficult to observe double refraction because the gyroscopic frequency eH/MC, which determines the relative delay of the two signals, would then be too small. From the other side, the frequency dependence of the effective altidude

$z' = \frac{1}{2} c \cdot \Delta t(\omega)$, t - time delay, ω- frequency of the reflected signal, indicates a complex variation in the electron concentration.

Extensive observations of the ionospheric altitude-frequency curves (ionograms) $z'(\omega)$ showed that under regular conditions the ionosphere has a well defined, stratified structure. The number of maxima, which changes under different conditions, gives the number of "layers." In the simple case the ionospere consists of the two layers: E-layer and F-layer. During daytime, particularly in the summer and at medium latitudes, the F layer breaks up into two - F1 and F2. Two layers, E1 and E2 can exist under certain conditions. In the lower ionosphere, under certain conditions, an absorbing D-layer appears during daytime. In many parts of the ionosphere there are frequent additional ionized formations, called "sporadic layers."

2.3 Radio Wave Propagation in the Ionosphere

The range of frequencies used in practice for communication, navigation and radar, as well as for scientific research, begins with the low frequencies $12\cdot10^3$-$15\cdot10^3$ Hz (wave length 25-20 km) and ends at 10^{10}-10^{11} Hz or more (centimeter and millimeter waves, i.e., already close to optical waves).

The transmission of radiowaves can only very rarely be considered as a propagation in free space, similiar to that

taking place in optics. Usually, we encounter a great variety of factors which complicate the structure of the electromagnetic field, such as the ionosphere, troposphere, the earth's curvature, and so on. Naturally, all these effects manifest themselves differently at different frequencies. It is advantageous to divide the radio spectrum into the following ranges:

Long waves (2000-20.000 m).

Medium waves (200-2000 m).

Short waves (10-200 m).

Ultra short waves (0.5-10m).

Microwaves (0.5 m or less, centimeter and millimeter waves).

However, many phenomena are physically identical even at different frequencies. The differences observed are the differences of "scale" only and are connected to the ratio of the characteristic scale of medium to the length or frequency of radio wave.

2.4 Effects of high power radio waves on the ionosphere

One of the most promising directions of the ionospheric research is connected with effects of high power radio waves on the ionosphere. Success in this direction could enable the management of the local interior structure of the ionosphere and directly influence the propagation of radio waves in the ionosphere.

Let's consider the problem as a whole. The modulated heating of the ionosphere by high power radio waves produces a fully developed Langmuir turbulence - so called artificial or induced turbulence [8-16]. This turbulence manifests itself as an artificial plasma line in the observed VHF/UHF radar spectra[14,15,21,22]. So far, the theoretical understanding of the developed turbulence is controversial. Weak Langmuir Turbulence Theory (WLTT) postulates the process as a cascade, where repeated parametric decay instabilities take place (3-wave

processes). This process continues until the intensity of one of the generated waves is below threshold for onset of a new decay instability. The application of strong Langmuir Turbulence Theory (SLTT) to HF (High Frequency) modification of the ionosphere explains the process as a large ensemble of localized, cyclic collapsing Langmuir cavitons [9]. They consist of high frequency Langmuir fields trapped in localized density cavities. The cavitons are dynamic entities with lifetimes of the order of 0.1 ms during which their spatial dimension "collapses from about 50 to about 10 Debye lengths" [1,14,23].

WLT theory, however, failed in many ways to provide a consistent explanation of many observed phenomena. [14]. For example, WLTT failed to predict the anomalously large Langmuir wave intensity. The observed altitudes of the most intense wave activities were consistently higher than predicted for freely propagating plane Langmuir waves satisfying the linear wave dispersion relation. Also, WLTT is not valid at the nominal radiated HF power used in experiments which exceeded the strong turbulence threshold. As a result, more realistic modelling of HF-heating process including WLTT and SLTT effects was developed [14].

The theory appears to explain the observed features of low duty cycle heating including power spectra taken with short time delays (< 30ms) from the onset of heating [14]. The spectral features at longer delays and in higher duty cycle heating may be explained in SLTT by two scenarios: One requires the development of spatio-temporal correlation between cavitons in overdense regions, presumably near reflection height. The other maintains the possibility under dense regions, of a decay cascade (free mode) Langmuir waves driven by conversion from enhanced ion fluctuations due to collapsing cavitons.

Many Soviet scientists are involved both in theoretical and experimental research. They study the dynamics of SLT theory using the well-known Zakharov's model [23,24] that describes the coupling of HF Laugmuir waves with low frequency (LF) ion

density fluctuations driven by a pump field. The equations of the Zakharov model can be written in the form [26].

$$\vec{\nabla}\cdot[i\partial_t\vec{E} + i\nu_e\circ\vec{E} + \vec{\nabla}^2\vec{E} - n\vec{E}] = \vec{E}_o\vec{\nabla}n \qquad (1a)$$

$$(\partial_t^2 n + 2\nu_i\circ\partial_t n - \vec{\nabla}^2 n) = \vec{\nabla}^2|\vec{E}_o + \vec{E}| \qquad (1b)$$

These equations couple the evolution of the slowly varying envelope of the Langmuir field, $\vec{E}o(t)+\vec{E}(\vec{X},t)$, to that of the fluctuation in the ion density "n" about its average value. Standard dimensionless variables are adopted in these equations and the total envelope field is decomposed into its uniform part $\vec{E}_0$ and its longitudinal nonuniform part $\vec{E}$. The dissipation is considered linear and local in $\vec{k}$ space (e.g. Landau damping), so that $\nu_e\circ$ and $\nu_i\circ$ denote convolution in $\vec{X}$ space.

The nonlinear term $\vec{\nabla}(n\vec{E})$ in Zakharov equations leads to the localization of Langmuir waves in density fluctuation or cavities "n". Under the action of the ponderomotive force, these localized states then nucleate and collapse.

This model of Langmuir turbulence with collision frequencies $\nu_i=\nu_e=0$ has collapsing caviton solutions [23] for dimension D=2 or 3. Collapsing cavitons transport electric field energy from their initial scales to shorter dissipative scales where Landau damping strongly dissipates the electric field. In order to simulate the long-time behavior of collapse, ν_e must increase faster than $k^{D/2}$ for large k in order for dissipation to arrest collapse [24,26].

Soviet and Swedish scientists in collaboration have conducted new experimental measurements of stimulated electromagnetic emission (SEE) excited in the ionosphere by a powerful high-frequency ordinary mode radio wave vertically injected from ground-based transmitter at frequencies f_0 near high harmonics of the ionospheric electron cyclotron frequency f_c [21].

The experiments were carried out during the daytime at the Sura ionospheric modification facility near Vasilsursk, 100 km east of Nizhny Novgorod (formerly Gorky) in Russia. Neglecting ionospheric absorbtion, the effective radiated pump power was approximately 270 MW, corresponding to a power flux of 0.3 mW/m^2 at a typical interaction height of 250 km in the F region. The experimental results concern the steady-state spectrum of SEE, attained after a few seconds of continuous pumping.

New experimental findings deal with the suppression of the commonly observed, down-shifted maximum (DM) feature in the stimulated electromagnetic emission (SEE) spectrum, excited by a powerful high-frequency pump wave in the ionosphere, for f_0 near harmonics of the ionosperic f_c. Studies of the SEE side bands have shown that in general the DM is most prominent when $f_0-nf_c \ll f_c$, where $f_c \equiv eB/2\pi m_e \approx$ 1.1-1.4 MHz, where e,B, m_e the magnitude of the electron charge, geomagnetic field, and electron mass, respectively. However, for small changes in f_0 very near nf_c, the SEE spectra change dramatically and in earlier experiments it was observed that the DM emissions were suppressed when $(f_0-nf_c) < 10$ kHz for n=3,4,5. New results show that the DM was suppressed for n = 4,5,6,7, and the DM emission disappears completely only when f_0 is varied within an extremely narrow frequency band of 100-200 Hz width corresponding to $f_0/f_0 \approx 2 \times 10^{-5}$.

The experimental results show that the properties of this feature are very sensitive to even a small change of pump frequency. For pump frequencies $f_0 \approx 7f_c$ the DM disappeared completely in extremely narrow range of aproximately 200 Hz. The results support the interpretation that the DM is excited by nonlinear interaction of upper and lower hybrid waves and that disappearance of the emission occurs exactly when the pump frequency f_0 passes through a harmonic of the local electron cyclotron frequency in the interaction region. The narrowness of the absorption resonance allows the determination of the local magnetic field magnitude with an accuracy of 1 nT. These experiments were supported by Radiophysical Research Inst., Nizhny Novgorod and Goran Gustafsson Foundation, Royal Swedish Academy of Sciences and Swedish Natural Science Research Council.

Some experiments indicate self-focusing oscillations or striations of the ionospheric plasma. [27,28]. The theory presented in [17,29] gives the explanation of these experiments and predicts new phenomena when a powerful radio wave beam propagates through the defocusing ionosphere. It is known that the ionospheric plasma can only act as a focusing medium at heights higher than 250 km. In a focusing medium the radio wave beam is unstable because of self-focusing processes that are associated with the development of oscillatory structures and striations in the plasma density and wave field amplitude[29]. In a defocusing medium the wave beam is stable. At lower heights (below 200 km) the ionosphere is defocusing. Oscillatory structure, however, can develop also in that case because of the strong nonlinear interactions processes that lead to significant changes of the intensity profile of the beam [29]. Gurevich and Stenflo [17] have presented solutions of the wave equations. They show that oscillatory structures will develop when a powerful radio wave beam propagates through the defocusing region of the ionosphere.

This propagation of a powerful radio beam in the ionosphere can be described by the wave equations [29], where the nonlinear properties of the dielectric constant $\epsilon=\epsilon_1 + \delta\epsilon_n$ play an essential role [17,29]. Here ϵ_1 is the dielectic constant in the absence of wave, while $\delta\epsilon_n$ is the nonlinear increment that is proportional to the wave intensity I. Wave equations can be written as:

$$\frac{\partial I}{\partial s} + \vec{\nabla}_\perp (I\vec{u}) = 0$$

$$\frac{\partial \vec{u}}{\partial s} + \vec{u}\cdot\vec{\nabla}_\perp\vec{u} + \beta\vec{\nabla}_\perp I - \vec{\nabla}_\perp \left(\frac{1}{2 I^{1/2}}\vec{\nabla}^2 \cdot I^{1/2}\right) = 0$$

where $\vec{\nabla} \equiv \partial/\partial\vec{x}_\perp$, s and $\vec{x}_\perp = (x\vec{x} + y\vec{y})$ are the coordinates in the direction of and perpendicular to the beam axis, respectively. They are here dimensionless because of normalizations ($kz \rightarrow s$ and $k\vec{r} \rightarrow \vec{x}_\perp$) with respect to the modulus of the wave vector. The wave

intensity I and the wave vector $\vec{u}$, which is perpendicular to the beam propagation direction, are thus functions of s and $\vec{x}_\perp$, i.e., $I=I(s, \vec{x}_\perp)$ and $\vec{u} = \vec{u}_\perp (s, \vec{x}_\perp)$. The nonlinearity parameter ß is defined as $\beta = -\delta\epsilon_n/2\epsilon_1 . I$

Then the mathematical methods which were developed to solve the nonlinear Schrodinger equation for a defocusing medium with positive dispersion have been used [17]. Thus, the asymptotic solutions of wave equations have been obtained. The evaluations according to the solution obtained indicate that the nonlinear defocusing process can significantly change the structure of a narrow beam with angle width less than 10^0, if the effective transmitted radio wave power WG, where W is the transmitted power and G is the antenna gain, is of the order of 100 MW. A wide oscillatory region will develop in which the wavelengths of the oscillations can be 100 m. In addition, the corresponding plasma density variations, which are proportional to the wave intensity, can be larger than 10%. It was noted that the present nonlinear defocusing process connected with heating of the ionosphere, also can occur at oblique radio wave incidence and can affect the self-focusing processes that occur at higher heights in the ionosphere.

Soviet scientists, and scientists from other countries conducted many experiments in which artificial ionospheric radio emission (AIRE) was recorded [8-12,9,30,31]. This emission arrives from the ionospheric region perturbed by powerful radio waves heating the ionospheric plasma and is concentrated in a spectral range of width ≈ 100 kHz near the pump wave frequency. The complex character of AIRE proves the presence of several mechanisms causing this phenomena. Thus, a decrease of plasma wave frequency due to induced scattering on ions was considered in [30,32]. This mechanism causes negative difference of the AIRE frequency relative to the pump wave frequency in agreement with basic features of the observed spectra. However, in some experiments [33] incoherent scattering is observed in the ion-acoustic part of spectrum as symmetric relative to the pump wave frequency.

So, in [16] another mechanism leading to AIRE with a symmetric spectrum is proposed. This mechanism considers the intensity and spectral features of AIRE caused by incoherent plasma wave scattering on density depression and cavitons, induced by nonlinear effects when power radio waves interact with the ionosphere. This approach gives the explanation for the appearance of AIRE in the range of large (>10kHz) positive shifts from the pump frequency.

Expressions for the total intensity of AIRE created due to incoherent scattering on cavitons have been obtained in [16].

$$\int \tilde{S}_{\omega}(t)d\omega/S_0(t) \approx (\pi\Theta/\Delta z)\cdot(\omega_0^2\ K/c\nu)^2\ \delta n^{(c)^2}$$

where $\tilde{S}_{\omega}$ - spectral density of flux of AIRE, S_0 - is the energy flux of the pump, K - anomalous absorption coefficient, $\delta n^{(c)2}$ - the density of relative fluctuations of electron density in the thermal inhomogeneities and cavitons, ν- electron collision frequency, Θ is the solid angle in which one can see the perturbed ionosperic region, Δz - the thickness of narrow plasma layer in the vicinity of the upper hybrid resonance of the pump wave in which intense excitation of plasma oscillations occurs on extended thermal inhomogeneities.

The analysis performed in [16] shows that incoherent scattering of plasma waves on cavitons yields the observed intensity of AIRE for quite small time dependent density perturbations $\delta n^{(c)2}/N^2=10^{-9}$, N - electron density, and easily explains the origin radiation of frequencies higher than the pump frequency.

Soviet Scientists have developed other approaches to explain the effects of high power radio waves on the ionosphere. These include the analysis of the excitation mechanisms of short period Alfven waves and vortices due to periodic heating of the ionosphere [34]. Results of numerical simulation of processes in the ionosphere induced by intense radio wave have been obtained [12]. It is known that an intense radio

wave undergoes strong anomalous absorption near the reflection from the ionosphere, transferring its energy to plasma electrons. It is important to know that at high altitudes - where the density of neutral particles is small-collisions with them cannot provide effective energy transfer from electrons to neutrals. Therefore, a substantial electron heating at these altitudes should then lead to the formation of strong heat fluxes travelling to the magnetosphere, as well as strong electron density pertubations within the whole magnetic force tube stemming from the heated region in the ionosphere.

A dynamics of artificial ionospheric turbulence during 1-500 ms period of time after the beginning of interaction of HF powerful radio wave (PW) and the ionospheric F - layer plasma is considered in [35]. It was shown that at this stage an essential influence on the interaction exerts the plasma density lattice formed near the height of PW reflection.

It should be concluded from the above that the research carried out by Soviet scientists in this field is of a high level and should be of interest to those cocerned with efforts to deliberately affect the ionosphere. However, the theories explaining the ionospheric phenomena are still not complete, and new experimental results could give additional information for theoretical investigation.

2.5 Theoretical treatment of wave propagation in the ionosphere

The theoretical methods for solving the problems of radio wave propagation in inhonomogeneous dispersive plasma can be divided into at least two groups which can be further subdivided: The first group consists of the different approaches for the description of wave propagation and scattering in deterministic media, the second - in random media. In addition, each group can

be divided according to the character of the problems to solve: linear or nonlinear, stationary or nonstationary, and so on.

Let us consider the first group of methods to solve the problem of determining electromagnetic wave field structure in plasma.

2.5.1 Geometrical Optics (GO) Method

It is well known that a number of important features of electromagnetic waves are described by the geometrical optics method (other names are the geometrical-optics approximation, ray approximation, eikonal method, multidimensional WKB method, semiclassical method) [3-5]. Furthermore, many problems of electromagnetic wave propagation may, at present, be solved only by this method: wave phenomena in media with travelling parameters, modulated wave propagation in dispersive media, the refraction and polarization phenomena arising in nonuniformly moving media and others. Governing the geometrical optics method is the basic principle that the solution of wave equations is seeking the form of "almost plane" and "almost monochromatic" waves.

$$E = \tilde{E}e^{i\varphi}, \quad D = \tilde{D}e^{i\varphi}, \quad B = \tilde{B}e^{i\varphi}$$

assuming that the amplitudes of wave field $\tilde{E}$, $\tilde{D}$, $\tilde{B}$, the local wave vector $\vec{k} = \nabla\varphi$, and the instantaneous frequency $\omega = -\frac{\partial\varphi}{\partial t}$ are varying sufficiently slowly in space and time [4].

Nevertheless, many problems are lying beyond the frames of geometrical optics: the behavior of the electromagnetic field in the vicinity of space-time caustics, quasi-optical description of wave packet propagation, optimal compression of modulated pulses, and others.

2.5.2 Fresnel's method

Classical works of Fresnel and Huygens, permitted for the first time, the theoretical analysis of the wave field structure. Fresnel showed the way to calculate HF wave fields as a sum of elementary waves (C/r)exp[ikr], where k is the wave number, r is the distance and C is unspecified multiplier. This produces a model of the wave field as an integral [6]:

$$I = \iint_{(S_0)} \frac{C\,(\alpha_1,\ \alpha_2)}{r} \exp\,[ikr]\, d\alpha_1\, d\alpha_2$$

where α_1, α_2 are the certain parameters on the surface S_0. The integral I, resulting from the sum of elementary waves, continues to validify the description of the wave field even in case when rays' field becomes irregular forming a caustic. Fresnel's approach does apply for scalar and vector, isotropic and anisotropic wave fields, in both homogeneous and inhomogeneous media. In addition, it works equally well within the vicinity of regular points of caustic and near singularity areas.

2.5.3 Uniform asymptotic expansion (UAE) method

Complex analytical functions are required to describe wave field structure in the vicinity of caustic. One of these functions, function Airy (t), helps to describe the wave field in the regular area of caustic [36,37]. In 1964 Kravtsov developed what was apparently the most sophisticated variant of such a description [38]. In Kravtsov's method the wave field can be expressed as anzats:

$$u = e^{i\omega t}\left[A v\left(-\omega^{2/3}\ell\right) + i\omega^{-1/3} B v'\left(-\omega^{2/3} m\right)\right]$$

Here frequency ω is a large parameter, l (x,y,z) and m(x,y,z) - functions to be specified, A u B are rows also to be specified with a coefficients depending on x,y,z. The use of the anzats of Kravtsov in the wave equation allows us to obtain eikonals $\tau = \pm \frac{2}{3} m^{3/2}$, where τ_- corresponds to rays approaching caustic and τ_+ - leaving caustic. Coefficients A and B can be determined from recurrent sequence of transfer equations. In 1966, the American mathematician Ludwig rediscovered anzats of Kravtsov [39].

The Kravtsov - Ludwig approach could be defined as uniform asymptotic expansion (UAE) method. UAE method was developed further [40-43]. In particular, a "swallow tail" caustic singularity was described [40]. However, UAE method requires a priori knowledge on rays' behavior, the placement of caustics in space and caustics shape. The shape of caustics specifies the functions within the anzats mentioned above. This requirement of a priori knowledge presents a serious drawback of the UAE method.

2.5.4. Maslov's canonical operator (MCO) method.

Maslov's method was first described in 1965 [44] and further developed later [45,46]. Recently a numerical representation of MCO method was worked out [47,48].

There are several difficulties in the application of MCO method to specific problems. First, the description of the wave field is carried out through integral from fast ocsillating functions. This in turn presents technical difficulties in calculation both numerically and analytically. Second, the wave field is described by different functions which depend on the position of the point of observation. In this case, one has to divide the

wave field into separate maps. This also makes algorithm more complex and calculations more dificult.

On the positive side, MCO method makes it possible to obtain so-called "special functions", which were recently named "wave catastrophy functions". These functions describe wave fields near all kinds of caustics. Thus, MCO method can bring one to Airy function (t), which describes wave field structure in the vicinity of the simple caustic [17].

2.5.5 Interference integral (II)

In 1972 Orlov suggested describing HF wave fields in smooth inhomogeneous media using integral of ray type [49] and caustic type [50] solutions in the form (2.5.2). This approach was named "interference integral (II)", and works for describing and calculating wave fields near any kind of caustics [51,52,53]. II method, like MCO method, presents a solution in the form of the integral of fast ocsillating functions. Only when these functions can be expressed in a clear analytical form is numerical calculation of II feasible.

2.5.6 Gaussian Beam Summation (GBS) Method

An asymptotic representation of wave field as an integral of Gaussian beams was first suggested by Babich and Pankratova in 1973 [54]. Using this idea in 1981, Popov developed a novel method for calculating wave fields in high frequency approximation, a so-called GBS method [55]. This method represents a wave field as a superposition of Gaussian beams. Gaussian beams, in their turn, represent the asymptotic solutions of initial wave equations. These elementary solutions are concentrated in a small vicinity of one isolated ray. Even in the areas of caustics, Gaussian beam has no singularities. Babich

and Nomofilov used a ray approach together with complex eikonal to build a Gaussian Beam [56, 57].

Let us consider formation of GB via the equation of Helmholtz

$$(\Delta + \omega^2 C^{-2})u = 0,$$

where u is a wave field, frequency ω is a large parameter, velocity C is a quite smooth function. The ray expansion in this case has the following form:

$$u = \exp(i\omega\tau) \sum_{j=0}^{\infty} \frac{u_j}{(-i\omega)^{j+2}}, \qquad \alpha = \text{Const}$$

Functions τ and u_j have to satisfy eikonal and transfer equations respectively:

$$(\nabla\tau)^2 = C^{-2}, \quad 2(\nabla\tau, \nabla u_j) + u_j \Delta\tau = \Delta u_{j-1}, \quad u_{-1} \equiv 0$$

It is conventional to call the characteristics of eikonal equation space-time rays. The solutions of these equations could be found in the form of asymptotic rows within a special ray-centered orthogonal system of coordinates [6]. The Gaussian Beam is found when solving an ordinary equation for coefficients of these asymptotic rows.

The advantages of GBS method are several: first, it doesn't depend on the presence or absence of caustics; second, it doesn't require calculation of special function; third, it permits calculating boundary problems, since GB could be reflected according to the

lows of geometrical optics; GBS method can be also extended to solve nonstationary wave problem using space-time Gaussian beams [4-6].

On the other hand, GBS method has some drawbacks. GB contains certain unspecified parameters, the correct selection of which determines the accuracy of subsequent calculations. Thus far, however, criteria for correct selection of these unspecified parameters have not been established. Moreover, the understanding of how to select parameters of GB is now controversial.

2.5.7 Propagation of waves in random medium

During the last few years great attention has been paid to the problem of studying propagation of waves in randomly inhomogeneous media. This problem has arisen when investigating different phenomena: diffuse reflection of radio waves from the ionosphere, so-called ultra-long-range propagation of ultrashort waves, incoherent scattering of radio waves in the ionosphere, twinkling of extraterrestrial radio emission sources due to the ionosphere and the interplanetary plasma, accuracy of measurement by radio methods of the coordinates of objects moving in the ionosphere or in the outer space, etc. Naturally, the abundance and variety of such problems have stimulated development and refinement of statistical methods for calculating wave fields propagating in a randomly inhomogeneous medium or passing through a layer of such a medium. The basic methods for treating this problem have been considered in [7,58].

It should be noted that, in practice, two types of problems arise: the direct problem in which one has to find the statistics of waves propagating in this medium from the known statistics of the medium and the inverse

problem, which consists in drawing conclusions about the properties of random inhomogeneities from the measured moments of the field (correlation functions, spectra, etc.). However, from the point of view of the theory these problems are equivalent, and, therefore, the relation between the two statistics is necessary.

2.5.8 Method of small perturbations

This method can be used when the medium is on the average homogeneous and stationary (i.e. $<\varepsilon>$=const, while the fluctuations are quasistatistical, i.e. $\varepsilon = <\varepsilon> [1 + \tilde{\varepsilon}(\vec{r})]$). But the theory can be extended to inhomogeneous and nonstationary meduim [58]. According to this method wave field u is expanded in a power series in $\sqrt{<\varepsilon>^2}$. If one can restrict to the first after u_0 term of series, this approximation is called Born approximation (BA). BA describes the so-called incoherent scattering of radio waves in the ionosphere and also describes ultrashort wave scattering by fine-scale turbulent inhomogeneities in the lower ionosphere [58]. When the characteristic scale of inhomogeneities increases, we must either take into account the later terms in the perturbation theory series or go over to another approximate method.

2.5.9 The parabolic-equation (PE) method

Method of smooth perturbations

Among the methods adapted to the case of large-scale inhomogeneities is the method of smooth perturbations (SP) proposed by S.M. Rytov [59] and the parabolic-equation (PE) method, which first was used by M.A. Leontovich [60]. The PE method suggests a slow transverse diffusion of the wave field energy with increasing x. This leads to the paraholic equation:

$$-2ik \frac{\partial U}{\partial x} + \Delta_{\perp} U = - k^2 \tilde{\varepsilon} U$$

where U is complex amplitude of the wave field u, $u = U(\vec{r})e^{-ikx}$, k = wave number, $\Delta_{\perp}$ is the transverse Laplacian.

The method of SP is distinguished by the fact that one introduces the complex phase $\psi = S + i\chi$ in place of U. Substituting $U = e^{-i\psi}$ into the parabolic equation gives the fundamental SP equation

$$2k \frac{\partial \psi}{\partial x} + i\Delta_{\perp}\psi + (\nabla\psi)^2 = k^2\tilde{\varepsilon}.$$

Expansion of the complex phase in the series

$$\psi = \psi_1 + \psi_2 + \ldots$$

where ψ_n is of the order of $\langle \tilde{\varepsilon}^2 \rangle$, gives rise to the system of linear equations of subsequent approximation [58]. One considers first the problem of the conditions under which one can limit the treatment to the first approximation ψ_1. This problem is not simple, and a large number of people have dealt with it, both in the Soviet Union and abroad [58].

Note that the most productive methods from the standpoint of concrete results are still the original methods: the method of small perturbations, the SP method, and the PE method. The general theory of multiple scattering provides a basis for the transport equation, but it is difficult to use it for solving concrete problems.

2.5.10 <u>Double passage effects</u>

A variety of fluctuation effects, owing to the presence of random inhomogeneities of the medium, arise when electromagnetic waves propagate in a real media [61,62]. Recently, it was determined that qualitatively new fluctuation effects, originating from the double passage

(DP) of waves through the same inhomogeneities, arise with backscattering.

Some anomalies in the behavior of the reflected wave, owing to the correlation of inhomogeneities on the forward and reflected wave paths, were first pointed out by Denisov [63]. Then, both Denisov and Erukhimov calculated the variance of the phase fluctuations of a normally incident wave reflected from the ionosphere [64]. From these calculations they indicated the effect of the doubling of the phase variance on the backward reflection of waves in a medium with large-scale random inhomogeneities. Another effect of double passage is "pure" enhancement of backscattering, discovered by Vinogradov et al. [61,65].

The existence of specific interference effects accompanying backscattering was indicated by Watson [66] and De Wolf [67]. Later, it was discovered that the backscattered wave has specific multichannel coherence and new and different (compared to the wave propagating without reflection) properties [61,62]. Although the DP effects have been known for many years, they continue to attract much attention because of their numerous new manifestations and applications.

The essence of "pure" enhancement of backscattering could be presented as follows: Let I be the average (over the ensemble of random inhomogeneity realizations) scattered field intensity at observation point, and let I_0 be the field intensity in the absence of inhomogeneities. It turns out that in case of backscattering, i.e., when the observation point consides with the source,

$$\bar{I} > I_0.$$

This inequality, established in [65], indicates that with the switching-on of inhomogeneities the mean backscattered intensity is unexpectedly enhanced. This backscattering intensity enhancement is due to the double passsage of the wave through the same inhomogenities of the medium. The magnitude of the effect is conveniently characterized by the enhancement coefficient $N(\rho) = \bar{I}(\rho)/I_0$, where ρ is the distance between observation point and source. In [65] it was shown that

$$N(\rho) = 1 + B_I(\rho),$$

where $B_I(\rho) = \langle\tilde{I}(0)\tilde{I}(\rho)/(I_0)^2\rangle$ is the correlation function of relative intensity fluctuations $\tilde{I}/I_0$ due to the single passage of the wave over the paths connecting the scatterer and receiver, and the scatterer and the source. Because of energy conservation, the enhancement N in the case of "exact" backscattering ($\rho = 0$) must be counter-balanced by some decrease in N, when the wave is "nearly" back scattered.

As a result, the backscattering indicatrix has a characteristic maximum at 180^0 ("exact" basckattering) and minima at angles close to 180^0[61]. The backscattering enhancement of radio waves can be observed in the randomly inhomogeneous ionosphere, which plays the role of a phase screen [65]. Double-passage effects must be taken into account in choosing the conditions for the optimal reception of signals from long-range sounding - in particular, the signals from backward-oblique sounding of the ionosphere in the short wavelength range ($\lambda \sim 10$-30 m) [62].

Multichannel effects are possible in the vicinity of caustics which are formed by radio waves with frequencies

below the critical frequency and reflected from the ionosphere [62].

2.5.11 Effect of EM wave penetration into the supercritical region

Various approaches developed in other theories can successfully be applied to radio wave propagation problems.

The nonlinear theory and quantum theory approach have been used for solving the very interesting and unusual problem of penetration of electromagnetic waves (EM) into the supercritical region of plasma [68]. It is well known [1,2] that EM waves are reflected by the inhomogeneous plasma layer (for example, ionospheric layer) when the frequency f_0 of incident wave reached the plasma frequency f_p, i.e. ($f_0 > f_p$). Thus, the problems of the penetration of EM waves into inhomogeneous plasma regions with local values of the plasma frequency larger than the frequency of the radiation incident upon the plasma (supercritical regions, $f_0 < f_p$) are of considerable interest both for the theory of wave propagation in plasma and for applied studies of plasma physics.

In the past, the penetration of strong HF waves has been studied [69-71]. Their action leads to a considerable nonlinear restructuring of the parameters of the medium. In particular, at the boundary between the vacuum and a uniform supercritical plasma, a modulated EM wave, incident from the vacuum, excites the electroacoustic waves [71]. The mechanism for trapping and entraining EM field packets by ion-sound waves into supercritical regions of an inhomogeneous plasma has been considered in [68]. Subsequent analysis has indicated that the transfer is caused by the existence, in inhomogeneous plasma with strong ion-sound waves, of EM field states which are

dragged along by these waves into dense plasma layers. The transport mechanism was demonstrated using as a model the problem of evolution of one-dimensional wave field $\psi(z,t)$, described in dimensionless variables by a Schrödinger type of equation:

$$i\frac{\partial\psi}{\partial t} + \frac{1}{2}\cdot\frac{\partial^2\psi}{\partial z^2} - U(z,t)\psi = 0$$

with a potential

$$U(z,t) = \frac{z}{2} + \tilde{V}(z-at),$$

where $\tilde{V}(z-at)$ is a low-frequency perturbation of the potential and moves with velocity $a>0$ into a region with large values of the stationary potential $U_0(z) = z/2$. This equation can be reduced through a change of the independent variables

$$\xi = z - at, \qquad t' = t$$

and of the required function

$$\psi = \bar{\Psi}(\xi,t)\exp(ia\xi - iat^2/4)$$

to the form

$$i\frac{\partial\psi}{\partial t} + \frac{1}{2}\frac{\partial^2\psi}{\partial t^2} + \left[\frac{a^2}{2} - \frac{\xi}{2} - \tilde{V}(\xi)\right]\psi = 0,$$

from which it follows that for the well- or hump-type perturbation $\tilde{V}(\xi)$ of the potential there can exist metastable states which are dragged into the region $z>0$.

$$\bar{\psi}_n = \bar{\psi}_n(\xi)\exp(-i\mu_n t - iat^2/4 + ia\xi),$$

with frequency $\omega_n = \mathrm{Re}\,\mu_n + at/2$ which increases monotonically with time. After the life-time of the metastable state $t_n = |\mathrm{Im}\,\mu_n|^{-1}$, an upwards shift by

$\Delta\omega$ of the order $a \cdot |\mathrm{Im}\,\mu_n|^{-1}$ is reached. The penetration depth of the field is then z_{pen} = $= 2\,\Delta\omega = 2a \cdot |\mathrm{Im}\,\mu_n|^{-1}$. The magnitude of the shift and the penetration depth are larger for low-lying weakly damped states. The equations for interaction of EM waves with the strong ion-sound waves in plane-layered plasma without external magnetic field are reduced to the form considered above. The coefficients for the excitation of such states are determined, as well as the life-time and the corresponding penetration depth of the field dragged into dense plasma layers.

The life-time of the "bunch" of EM field itself is

$$t_K = \frac{L}{c_s}\left[\left(1 + 2\frac{c_s t_s}{L}\right)^{1/2} - 1\right],$$

where L is the width of linear plasma layer with electron density

$$N(z) = N_0\left(1 + \frac{z}{L}\right),$$

$t_s = \nu_{eff}^{-1}(z=0)$ is the life-time of the "bunch" in its initial position, ν_{eff} - effective collision frequency in plasma, $t_s = 5 \cdot 10^{-2} T^{2/3}$, $c_s \approx 10^4 T^{1/2}$, k - the index of corresponding state.

Gromov and Talanov conclude that the entrained field can be dragged into plasma layers with a local value of the density several times larger than the value of the plasma density in the trapping region. For example, for plasma parameters $T_e \sim 5 \cdot 10^5$K, $N_0 = 10^{14}$ cm^{-3}, $L \sim 10$cm, the "bunch" has penetrated together into the region with density $(N_k/N_0) \sim 5.1$, and the life-time t_k is then of the order of $1.9 \cdot 10^{-6}$s. The frequency of the "bunch" increases proportionaly to $(N_k/N_0)^{1/2} \sim 2.3$

Thus, the mechanism proposed in [68] indicates the possibility of EM waves penetrating into a supercritical

plasma at an appreciable depth, which is undoubtedly of interest for transporting EM field energy into dense plasma layers.

2.5.12 The development of the theory of EM wave propagation in the ionosphere

The further development of the theory of EM wave propagation and its application to the ionosphere have been carried out in different directions.

The generalization of Huygens' principle (part 2.5.2, present report) to a wide range of HF difraction problems has been considered in [72]. The substance of the suggested method is to represent the initial conditions for the smooth wave surface by the superposition of "generalized" nearby point sources. The sources are represented as spread and overlapped Gaussian beams with the cross-section of the order of $\sqrt{\lambda H}$, where λ is the wave length and H is a characteristic scale of dielectric permitivity variation. Thus, the source size tends to zero when $\lambda \to 0$.

The superposition of Gaussian beams at any point describes the exact asymptotic of the diffraction problem. In this case the solution obtained has no singularities in the focal regions of any complexity.

The original numerical integration method and WKB methods (2.5.1) are used for the calculation of wave fields generated by a loop magnetic antenna in the ionospheric plasma [73]. The full-wave calculation of the VLF propagation through the lower ionosphere is added to find amplitudes on the earth. Numerical results have been obtained for frequencies 5-30 kHz. These results

illustrate the general features of wave field structures in the ionosphere and on the Earth's surface.

The generalization of Rytov's method (2.5.9) to the case of inhomogeneous media and HF propagation and scattering in the ionosphere is presented in [74].
Asymptotic integral representation for the point source field in a stratified media with local irregularities is proposed [74]. The field is expanded into an integral in plane waves propagating in the inhomogeneous media. Each elementary wave is described by the first approximation of perturbation theory (2.5.9) for the complex phase. The method developed is used for solving some deterministic and statistical problems of HF propagation in the ionosphere. Zernov et. al. consider the problem of diffraction over the local ionospheric irregularities, including such aspects as the ambipolar diffusion mechanism, multibeam effects, doppler shifts, focusing of the field on caustics and their destruction.
The calculations of the power spectra of the field phase and amplitude fluctuations on a single lop path due to electron density irretularities are also presented. These calculations are compared with the results of experimental investigations.

The phenomena of resonant transition radiation in boundary plasma layers is considered in [75]. An effect of considerable order of magnitude - enhancement of resonant transition radiation in strongly inhomogeneous layers with nonlinear profile - was observed on the boundary of an overdense plasma. Structural effects of transition radiation are investigated in boundary layers of an equilibrium or inverted plasma.

Classical nonlinear dynamics and chaos of rays are considered in problems of wave propagation in inhomogeneous media [76]. The geometrical theory of wave propagation in regularly inhomogeneous waveguide media is discussed from the point of view of nonlinear Hamiltonian dynamics. The trajectory of rays is described, defining the connection between the structure of the wave front and the dynamics of rays.

The development of the interference integral (II) method (2.5.5) and its application to statistical problems of ionospherical radio wave propagation is presented in [77]. Considering HF propagation in the random inhomogeneous ionosphere, it is necessary to note its peculiarities:

1. ionospheric radio waves often have strong fluctuations due to random caustics;
2. there are regular caustics, skip-distance and maximal usable frequency (MUF) connected with the regular refraction of ionospheric radio waves. The presence of the random ionospheric inhomogeneities results in the intensification of the wave field in caustic shadow and for radio wave propagation above MUF;
3. there is a scattering by a rough earth surface in the vicinity of caustic for oblique multihop propagation and backscatter sounding.

These problems are solved using the interference integral method [77]. A scintillation index formula is obtained for strong fluctuation of the oblique ionospheric radio wave. Those aspects which are investigated are the following: mean intensity, spatial and frequency field coherence functions, mean pulse signal form in and above the vicinity of MUF when taking into account random

ionospheric inhomogeneities, a rough earth surface and caustic focus in skip-distance.

2.6 Ionosphere data processing

The experimental investigations of the ionosphere are based on a theoretical understanding of the problems of complicated ionospheric processes and the interaction of EM waves with the ionosphere. In turn, the experimental results stimulated the development of new theoretical research of the ionosphere and the appearance of new theories explaining the ionospheric data.

Rocket and satellite observations provide an understanding of many ionospheric phenomena and yield new information to stimulate the development of the theory explaining these experiments. Thus, substantial progress in the understanding of the interaction processes between the electromagnetic fields and ionospheric plasma has recently been achieved due to new experimental data on the fine structure of the fields and particle fluxes in the auroral zone [78].

Measurements on the satellite Intercosmos-Bulgaria-1300 (IC-B-1300) have shown that discrete fluxes of low energy electrons and suprathermal ions are often related to nonlinear Alfven waves. The results from the IC-B-1300 satellite support the kinetic Alfven mechanism which has been discussed by several authors [78]. They discussed the possibility of a transition from the laminar to the turbulent convection regime, accompanied by the splitting of convection into external magnetic field-aligned current vortices. These vortices can be considered as finite amplitude Alfven waves. At a definite transverse

wavelength, oblique Alfven waves excited in the ionosphere can be trapped within the ionospheric resonator, which is limited by the E-layer at the bottom, and the anomalous wave absorption zone at an altitude of the order of 10^4 km at the top. A one-dimensional model was used to describe nonlinear oblique Alfven waves. The calculations have been performed for a homogeneous plasma in the aproximation $m_e/m_i << \beta << 1$ (where $\beta = 8\pi/B^2$ is the ratio of plasma to magnetic pressure, and m_e/m_i is the electron to ion mass ratio). This condition is not fulfilled in the auroral plasma at altitudes of up to at least 10^4 km. In addition, the characteristics of the strong electromagnetic burst polarization show a need for a two-dimensional analysis of the field structure. Therefore, in [78] the authors investigated the nonlinear set of equations for the kinetic Alfven waves in a slightly inhomogeneous cold ($\beta < m_e/m_i$) and hot ($m_e/m_i < \beta < 1$) plasma for vector fields, and presented a theory for nonlinear drift-Alfven wave structure.

The three kinds of solutions which were obtained describe three types of two-dimensional vortex formations in the magnetospheric and ionospheric plasma: dipolar drift-Alfven vortices, two-dimensional vortex chains and monopolar (axisymmetric) vortices. The interpretation of the peculiarities of the behavior of the particle flux and the main characteristics of the small scale electromagnetic disturbances were given within the framework of this theory.

It is assumed that the Alfven vortices observed in the ionosphere at altitudes of 850 km are generated in the plasma sheet boundary layer region or at the inner edge of the plasma sheet where substantial space gradients of

the plasma pressure (density) have been found and from where they can transport trapped particles to the auroral ionospheric region. The penetration of the vortices into the ionospheric plasma region is possible due to tunnelling through the transition layer where the wave dispersion sign changes.

The process of transition from quiet uniform auroral areas to active rayed forms can thus be explained by means of the theory for drift-Alfven waves. When the plasma inhomogeneity exceeds a certain threshold value, the energy of the vortex tubes becomes negative. This results in an explosive "condensation" of the plasma into vortex filaments. The theoretical treatment that is carried out in [78] and considered above is in reasonable agreement with the experimental observations.

Great attention in Russian ionospheric research is paid to the investigation of ionospheric irregularities. Diagnostics of the electron density irregularities caused by plasma turbulence is considered in [79]. Turbulence in the ionosphere quite often results in the appearance of extensive layers, filled by electron density irregularities. The theory of stastistical properties of spatial structure tomographic reconstruction is proposed for a randomly nonhomogeneous turbulent plasma. Equations obtained for the measured field coherency function make it possible to determine the layer coordinates and the cross-sections of the correlation function of electron density fluctuations.

With the help of a transmitter aboard a moving satellite and a linear receiving array on the ground, for a statistically homogeneous layer, it is possible, given a set of two-dimensional cross sections, to obtain a

three-dimensional correlation function structure. A pointer receiver allows one to reconstruct a two-dimensional correlation function cross-section. Results of the experiments have been obtained for the layer identification and the determination of correlation function cross-sections and their two-dimensional spectra.

Other approaches for a tomographic reconstruction of travelling ionospheric disturbance parameters are proposed in [80,81]. A tomographic method was considered in order to reconstruct parameters of an inhomogeneous ionosphere on the basis of model representations using angles of arrival and total electron content [80]. Signals can be generated by passing satellites. A simulation of angles of arrival was performed with the purpose of checking the ionospheric parameter reconstruction algorithm for its capabilities. With the magnetic field taken into account, this test employed a ray-tracing program in a three dimensional inhomogeneous medium. In this program, a system of six differential equations was used to calculate the angle-of-elevation and azimuthal corrections which served as the input data for the tomographic reconstruction algorithm. The opportunity to correct radioastronomical signals was demonstrated. [81] indicated that using methods of ionospheric tomography for satellite signals makes it possible to reconstruct large-scale structures of the high-latitutde ionosphere such as the main ionospheric trough. The best space-and-time resolution was achieved in the case of a combined treatment of data from standard ionospheric stations and from satellite signal reception sites. The analysis has been made using modelling methods on the basis of experimental data from a meridional chain

of ionosphearic stations located in the latitude range 56-70^{0}N.

The results of the study on the space-time structure of wave disturbances are presented in [82]. These results have been obtained for F-region electron concentration, based on frequency observations of some stations of vertical sounding of ionosphere located in different regions of the Soviet Union. The WITS period of the measurements of the ionosphere on March 16-20, 1988 was examined and the results of spectral analysis which were obtained during this time interval indicated the dynamics spectrum of plasma frequencies at various fixed heights. These conclusions characterized the space-time distributions of the F-region electron concentration following a solar terminator during morning hours.

[83] considers the effects of travelling ionospheric disturbances (TID) according to measurements of radio signal characteristics. These TIDs are generated by magnetospheric disturbances and contribute to the angular and Doppler characteristics of radio signals recorded on a latitudinally-directed radio line. The 15.07-MHz signals of the transmitter near London, recorded at Kaliningrad (1450-km line) were analyzed. The radio-signal characteristics are theoretically estimated for a given model of the ionosphere with allowance for its inhomogeneous space-time structure. This structure is a superposition of the variations of large-scale TID arriving from the north and regular temporal variations associated with the daily pattern. Ivanov et. al. conducted a comparison of the recorded radio-signal characteristics on a quiet and a disturbed day and reached an agreement between experimental results and computation using a three-dimensionally inhomogeneous model. The results indicated, that the large-scale disturbance propagating from the north was dominant in the reflection region.

Ionospheric irregularities influence all kinds of ionospheric data, including ionograms. Common techniques of determination of N(h)-profiles from ionograms give good results in case of the

stratified ionosphere. However, in the presence of N_e distribution disturbances, ionograms became very sophisticated [84]. This work deals with results of ray-tracing modelling of ionograms observed in the presence of local ionospheric irregularities. In particular, emphasis was placed on single large local irregularities and multiple weak irregularities.

Analysis of the shapes of ray trajectories and the correspondent tracks on ionograms enables us to determine 3-dimentional N_e distribution in a model approximation from many component ionograms. Small-scale irregularities of electron concentration can cause the scattering of Z -mode waves [85]. A number of features of topside ionograms are interpreted as a direct transformation of ordinary waves into a wave of extraordinary polarization (Z-mode) associated with scattering at natural small-scale irregularities of electron concentration. This mechanism explains the anomalous absorption of ordinary waves within the ionosphere. The global distribution of small-scale irregularities, based on mapping of amplitude, presents a scattered signal registered on topside ionograms of Cosmos-1809 satellite.

Experimental data received on the network of HF radiopaths can be used to diagnose and forecast a high latitude ionospheric radiochannel [86]. It is possible to make long or short-term predictions on the basis of the signal model at the channel output. Such a model must include the parameters of the signal fading, signal amplitudes, some characteristics of stationarity, signal spectra and some parameters of the oblique sounding of the ionosphere. In order to make short-term forecasting one must have in addition some real time information about signal parameters simulataneously with data of oblique and vertical sounding of the ionosphere from several radiopaths. The present investigation is connected with this approach to identify such phenomena as magnetospheric substorm, main trough of ionization, daytime cusp, etc.

The procedure for calculating the scatterd field level in the service region for the case of radio broadcasting in the shortwave band is examined in [87]. Under certain conditions the received signal level is at a maximum in the skip zone and may be significantly higher than in the irradiated zone.

The statistical characteristics of the first dead zone for decameter wave propagation in the ionosphere have been obtained in [88].
VLF (very low frequency) data analysis allows one to study the D - region of the ionosphere [89, 90].

[82] determines phenomena which are traditionally joined together under the title of the "winter anomaly," three different mechanisms of meteorological control of the D- region. VLF data analysis shows that electron density variations at middle latitudes may be caused by:

a) polar air mass transport down to 45^{0} of latitude;
b) vertical transport enhancement at latitudes between 37^{0} and 51^{0} due to low-latitude stratospheric anticyclone development and expansion;
c) vertical transport changes related to the seasonal reversals of the zonal wind and stratospheric warmings.

VLF steep-incidence data obtained at two different locations during the solar eclipse of 31 July, 1981 provides an opportunity to study the D-region response to the event [90]. To specify the role played by solar radiation in the ionospheric ionization budget, the D-region behavior during the eclipse was compared to what it would have been in normal twilight conditions. An empirical relation has been obtained which made it possible to use the electron density profiles measured at large zenith angles of the sun in the dusk for modelling the eclipse effects.

VLF observations of the eclipse proved rather helpful for explaining differences in the previous results on the D-region electron density distribution obtained by rockets for several solar eclipses.

[91] developes the quasianalytical theory of the propagation of the zero-mode of VLF waves (0,5-10) kHz in the Earth-ionosphere waveguide. This theory takes into consideration the dependences of conductivity in the waveguide with the height, the anisotropy of the near-Earth plasma and the transformation and interaction of the waves of different polarization. The theoretical calculations of the attenuation of these waves in the waveguide obtained for different frequencies agreed with the numerical and experimental results.

Some experimental effects such as the semitransparency of the ionospheric sporadic layers, multiple reflections, oscillations of the reflection coefficient modules, etc., can be explained using the approach suggested in [92]. These effects had no adequate interpretation prior to this study in 1990 which uses algorithms and programs,to effectively calculate the reflection coefficients matrix for different normal waves components in a wide frequency range and to determine radio signal distortions and radio wave fields. Electron density and collision frequency profiles may be arbitrary. It is shown that, for the case of reflection from a layer with a "valley," the reflection coefficient phase derivative with respect to frequency has sharp maxima. Such effects of "resonances in group delays" is related to the interference due to the tunnel-effect and overbarrier reflection.

The results of experimental investigations of the ionosphere have led to a more accurate model of the structure of the lower ionosphere (below the maximum of the F_2 region). The experimental data on the outer ionosphere (above its principal maximum) obtained with the aid of satellites and rockets are very interesting. These results, however, are not as yet sufficiently complete and require additional refinement. Similary, data on the statistical nonhomogeneity of the ionosphere, although based on more extensive investigations, must still be regarded as preliminary. It is very difficult to discover the mechanisms responsible for the observed phenomena, and consequently,

there is some uncertainty as to the interpretation of the corresponding experimental data.

2.7 Ionosphere modelling

The problem of ionosphere modelling is largely a problem of ionosphere formation, i.e. calculating the ionization balance in the upper atmosphere whose properties change appreciably with altitude. To solve the problem of the ionization of the atmosphere, it is necessary to know its physical state, i.e. its composition, temperature, density at different altitudes, as well as the altitude dependence of the intensity of solar ultraviolet and X-ray emission, the character and quantitative data on various micro-processes, inelastic and partially elastic collisions between charged and neutral particles, etc. Meteors, corpuscular and other radiation streams reaching the earth's atmosphere,as well as solar and magnetic activity play an important part in the ionosphere. The problem of ionosphere modelling, expecially a global modelling, is thus very complicated and has not yet been resolved despite of extensive theoretical and experimental work.

Various models for ionospheric phenomena and different ionospheric parameters co-exist, and the superposition of these models creates a description of the ionosphere as a whole. For example, International Reference Ionosphere (IRI) can reproduce the typical day and night electron density profile in the middle ionosphere using a linear combination of four LAY-functions, developed by Rawer [93].

The ionosphere model, designed by combining the empirical and determinative approaches, is proposed in [94]. This model describes the ionosphere at the altitude of 100-500 km. Using the world-wide vertical sounding experimental data as initial values Polyakov et. al. created the global maps of the major ionospheric parameters (foE, foF_2, hmf_2). These maps were called the empirical part of the model.

The vertical distribution N(h) on any point of the earth is found by means of solving the continuity equations for ions $O+$ and molecular ions $M+$. This is the theoretical (or determining) part of the model. The data of the empirical part are used for corrections of the determinate part of the model. This model describes all levels of the sun's activity and the seasons and covers a wide range of the middle and equatorial latitudes and polar regions. This model was used many times for computations of different radio path parameters. These computations were successfully realised by means of various methods of radio wave propagation.

The mechanisms of the longitudinal variations of the subauroral ionosphere structure, of the mid-latitute F-layer height and concentration, of the position of equatorial anomaly crests, and ionospheric parameters over the geomagnetic equator are considered in [95]. The analysis is based on the topside sounding data from the "Interkosmos-19" satellite for high solar activity. The solution of the inverse problem for night mid-latitude ionosphere shows that the longitudinal variations of h_mF2 and N_mF2 on a fixed geomagnetic latitude are mainly determinded by the effect of the zonal component of neutral wind due to longitudinal variations of the geomagnetic field declination and by the effect of meridional components due to its amplitude dependence on geographical latitude.

The model of the E/F region valley is proposed in [96] describes the phenomenon of the E/F -region valley in the height profiles of auroral ionosphere electron density which has not yet been completely understood. Very definite distinctions exist between the E-region behavior in the mid-latitude and the auroral ionosphere. [96] deals with the analysis of EISCAT CP1-data for a period of increased magnetic activity. It was found that the main peculiarity of the auroral ionosphere is a rapid appearance of a deep valley between E and F regions just after the magnetic disturbance development. The height of maximum decrease of electron density in this valley is proportional to the AE-index value and can reach heights of 230-240

km. Possible physical mechanisms are considered which can cause such changes of the electron density profiles, e.g. the ratio of atomic and molecular ions in the auroral ionosphere changed significantly during netospheric substorms. Consequently, a height distribution of recombination coefficients would also be different. Corresponding model calculations of the vertical profile of recombination coefficients showed that in the E-region they increase approximately two-fold during a substorm. Thermo and electrodynamical processes must also be taken into account in the formation of the E/F valley.

[97] considers the theoretical model of effective dissipation of radiowaves in aurorae. The results present the theoretical analysis of anomalous absorption of radio waves in the auroral ionosphere related to intrusion of energetic electrons (i.e. in aurorae). The theory uses the Plasma-Turbulent Layer (PTL) to explain, in particular, the radioaurorae double-peaked altitudinal structure. It is shown that effective dissipation of radio waves can be explained by both nonlinear mode coupling in turbulent plasma of the upper sublayer and by O-Z transformation on small-scale field-aligned fluctuations of electron density in the lower sublayer. The characteristic decrements of dissipation are estimated for the typical parameters of aurorae.

The empirical model has been used to draw a map of maximal electron density distribution for the F2 layer in the Northern hemisphere corresponding to solar-geophysical conditions for two SUNDIAL periods: March 10-20 and December 5-10, 1988 [98]. The model values of the critical frequencies and the F2 maximum heights have been compared with ground-based ionospheric data for these periods. Within the day-time sector, the mean error at all latitudes in question ($\Lambda = 45^{0} \div 65^{0}$) is 10-15% in frequency and 10-15% in altitude. The accuracy of the model calculations depends very much on the accuracy of the trough position and the determined configuration. If the latitude of the real trough position departs from the model estimation by more than 1^{0}, the error in the subauroral region may exceed 200%. Also, the accuracy of the $f_{0}F2$ model estimations in the night-time sector increases

significantly if the effect of the interplanetary magnetic field on the trough position is taken into account.

Effects of the main ionospheric trough on HF radio wave propagation are considered in [99]. Zhulina et. al. computed HF wave propagation characteristics (angles of arrival, energetics and hop distance) for paths traversing the main ionospheric trough. The trough is described by the SMI-88 and IRI-86 models and by IK-19 satellite data. The reliability of the above models in the trough region was estimated, and the analysis of the obtained characteristics has demonstrated a number of features associated with the trough depth and location with respect to the wave reflection region. In particular, in the presence of the trough, the arrival angles are observed to be greater by 10-15^0 than the emission angles. The trough results in the signal field attenuation of up to 10-15 dB (in terms of the equivalent emission power).

The range-azimuth distribution of auroral backscatter echoes received at Essoyla at frequencies of 93 and 45 MHz is predicted for a model which includes the effects of electron density magnetic aspect angles, and the azimuth of current flow, and also takes into account ionospheric refraction [100]. These predictions are supported by observations made at Essoyla.

The distribution is in the form of an arc with maxima of backscatter in both eastern and western wings. As the electron density increases, the intensity of the backscatter increases more rapidly and the azimuths of maximum backscatter separate even further. For currents flowing along the L-shells, the backscatter is strongest in the eastward wing.

In conclusion, please note that the list of theoretical methods presented in this review is not complete. Not all the problems connected with the ionosphere are reflected here. Some additional theories which could be applied to the problems of radio wave

propagation in the ionosphere are not covered by this report. Nevertheless, from the point of view of further ionospheric research, the most important methods to be developed and the problems to be solved are covered in this present review. In general, therefore, this work conveys the current state of Russian research in the field of radio wave propagation in the ionosphere.

CHAPTER 3:

SPECIFIC PROJECTS,

Based on a visit to Russia

The following part of the report describes a variety of specific Russian projects in the field of radio wave propagation in the ionosphere. These projects reflect the possible directions of the theoretical and experimental research conducted in leading Russian Institutes and their expected results.

3.1 Effects of high power radio waves on the ionosphere

"Sura" heating facility

Modern tendencies to research near-Earth space demand a complex approach for obtaining the full information about parameters of neutral and ionized shells of the earth. Such problems have been formulated in important international projects STEP (Solar-Terrestrial Energy Program) and the International geosphere-biosphere program "Global Change". To solve these problems, it would be tempting to combine the measuring facilities and the high quality specialists into a single research center. The modified "Sura" facility has been organized on the model of two institutes in Nizhny Novgorod - the Radiophysical Research Institute (NIRFI) and the Institute of Applied Physics of the Russian Academy of Sciences (IPFAN) - and could function as such center.

Internationally, research on heating the ionosphere by powerful radio waves is carried out at the following facilities: Arecibo, Puerto Rico (operating frequency f_0=3÷12 MHz, effective power PG∼160÷300 MW, latitude 18^0N), Tromsö, Norway (f_0=2,5÷8 MHz, PG∼360 MW, 70^0N) and Fairbanks, Alaska (USA).

All these facilities complement one another. The "Sura" ionospheric modification facility (f_0=4,785÷9,310 MHz, PG ~ 150÷270 MW) is described in detail by Belov et al. (1983) [101]. It is located at 56.13^{0}N and 46.10^{0}E at the confluence of the Sura and Volga rivers near the village of Vasil'sursk (100 km east of Nizhny Novgorod). Sura is the only mid-latitude facility in the whole world that has unique possibilities for the investigation of both ionospheric and magnetospheric processes [102]. In perspective Sura can be used as a magnetosphere radar [102,103]. Sura has been chosen for many research projects dealing with the investigations of the ionoshpere and magnetosphere. Some of these projects and research groups are presented below.

3.1.1 Research Program of Upper Ionosphere Irregular Structure (Ionospheric Turbulence) and its Influence on Radio Wave Propagation

Principal investigator: Prof. Lev M. Erukhimov, Radiophysical Research Institute (NIRFI), Nizhny Novgorod, Russia.

Research group: 9 Ph.Ds in physics and mathematics (A.F. Belenov, G.N. Boiko, S.M. Grach, L.M. Kagan, G.P. Komrakov, E.N. Myasnikov, E.N. Sergeev, V.L. Frolov, P. I. Shpiro).

Goal: The creation of a physical model of ionospheric inhomogeneities for the prediction of radio wave propagation.
Experiment: Modelling of natural ionospheric turbulence with the help of ionospheric F-region modifications by powerful radio waves [21,104-106]

("Sura" heating facility), so that the following research methods are possible: field aligned scattering, the anomalous absorption of radio waves reflected from the modified ionosphere, multifrequency Doppler soundings of the ionosphere, stimulated electromagnetic emission measurements, and measurements of radio scintillations of radio signals from satellites.
Measurement techniques: the "Sura" heating facility.

The theory: The creation of theoretical and numerical models of ionospheric turbulence of artificial and natural origin and the diagnostics of turbulence parameters according to experimental data results which follow. This research is proposed in order to study the typical features of the origin of artificial ionospheric turbulence, its development and relaxation; thermomagnetic phenomena in the high latitude ionosphere; radio signal statistical characteristics, propagating through the medium with random irregularities, including reflection of radio waves reflection from the ionosphere.

3.1.2 <u>Control the Long-Distance Radio Wave Propagation Through Output (Input) of the Signals from the Ionospheric Waveguide by Means of Ionospheric Modification</u>

Principal investigator: Dr. V. Uryadov (NIRFI).
The research group: 4 Ph.Ds (V. Ivanov, N. Ryabova, N. Mityakov, G. Komrakov).

Goal: Definition of natural ionospheric conditions and optimal parameters of the ionospheric modification by powerful radio waves which is necesssary for input/

output of the signals into the ionospheric waveguide (IW) [107, 108].

Planning:

1. Design algorithms and software for the calculation of characteristics of radio wave propagation in the IW.
2. Experiments on input/output of the signals into the IW using the "Sura" facility and the oblique chirpsounder.

3. Comparison of predictions and experimental data on input/output of the radio signals.

3.1.3 <u>The Research of the Interaction Between Magnetic Field and Plasma Disturbances in the Ionosphere</u>

Principal investigator: Dr. A. F. Belenov (PhD, NIRFI)
Number of participants: 3

Project location: Radiophysical Research Institute (NIRFI, B. Pecherskaya Str. 25 N. Novgorod 603600, Russia), Institute of Radio Astronomy (Krasnoznamennaya Str. 4, Khar'kov, 310002, Ukraina)

Experiment: The investigations of the effects of reverberative scattering [109] and quasi-periodic Doppler shift [110] simultaneously with magnetic field measurements.

Method of the investigations: The bistatic radar experiment using unique phase antenna array UTR-2 (Khar'kov, Ukraina) and "Sura" heating facility (Nizhny Novgorod, Russia).

Theory: The interpretation of the reverberative scattering effect possibly based on the model of the Pc-3 generation.

GOAL: the creation of the remote diagnostic technique for magnetic pulsation measurements using HF bistatic radar.

The results of simultaneous HF scattering and magnetic measurements demonstrated the reality of this project.

3.1.4 ELF-VLF Radiation from an Ionospheric Antenna Caused by Powerful Ground Based HF Transmitters

Principal investigator: Prof. Victor O. Rapoport (NIRFI).
Research group: 2 PhD.: Dr. D.S. Kotik and Dr. L.F. Mironenko (NIRFI).

One of the most interesting phenomena produced by powerful HF radiation in the ionosphere is the generation of ELF-VLF emissions. The effect of the VLF generation was first discovered in the early 70s by a group of NIRFI scientists. [111]. During the last 15 years, these effects underwent intense investigations at the Tromse heating facility, as well as at Aresibo. Several problems, however, remain unsolved and these they propose to investigate.

1. Detection of the ELF-VLF emission caused by modulation of the quasistatic current in the ionosphere F-region due to anomalous resistance produced by parametric instabilities.

2. Investigation of the Cherencov radiation from the lower ionosphere super light source on the earth - Ionosphere waveguide produced by the sweeping beam of a powerful transmitter.

3. Investigation of ELF radiation by cubic thermal nonlinearity using two powerful transmitters.

3.1.5 Electro-Acoustic Sounding of Atmospheric Active Zones

Principal investigator: Prof. Victor O. Rapoport.
Research group (4): N. Belova, E. Dorfman, Yu. Fedoseev, V. Zinichev.

The aim of the present project is to investigate the electric phenomena at heights of 2-10 km. This extremely variable region of the atmosphere contains substantial atmospheric energy and is prominent in the constitution of weather phenomena. The main active atmospheric zones such as frontal discontinuities, cyclonic and thunderstorm centers, etc. are developed at these heights. An evolution of the active zones determines, to a great extent, the dynamics of atmospheric processes of various scales.

The problem inherent in the measurement of atmospheric electric parameters causes special difficulties. Contact methods using sounding balloons and aircraft laboratories have a nubmer of principal drawbacks: they introduce considerable distortions in the fields being measured and give information only in the vicinity of the device motion trajectory that is absolutely insufficient for the present-day level of investigations. There are almost no methods for remote

sounding of atmospheric electric parameters at the present time. An exception are the radar investigations of lightning discharges, but these provide only a fraction of information on the development of thunderstorm centers as a whole.

The researchers expect to conduct, for the first time, the electric-acoustic sounding of the electric parameters of the cloudy atmosphere on the basis of the resonance of the sound wave and the electric cells, and the turbulence of the cloud-containing charged aerosols. This resonance leads to the appearance of a macroscopic electric dipole moment at the frequency of the sound radar (with a scale of about the size of a sound pulse envelope), where the electric field extends far above the cloud boundaries and can be measured at the Earth's surface. The electric-acoustic sounding reveals the principally new means of remote sounding of the electric structure of thunderstorm cloud and, in particular, electric cells, which are important for our understanding of atmospheric processes [112-114].

On the basis of the above, let us now estimate the amplitude of a ground level electric field.

$$\bar{\mathcal{E}} = \left(2I_{\Omega}\sqrt{(\Delta\Omega)^2}\right)^{1/2} \approx \frac{2\pi}{\Delta k_{\perp} h^3}\left(\frac{\Delta_{\parallel}}{\Delta k_{\parallel}}\right)^{1/2} \cdot \left(\frac{W_a}{\rho h c_s^3}\right)^{1/2} \cdot e_0 \quad (1)$$

where $\Delta k_{\parallel}$ and $\Delta k_{\perp}$ are the characteristic scales of the spatial spectrum of electric cells, e_0 is the amplitude of the electric cell. Assuming $\Delta k_{\perp} \sim \Delta k_{\parallel} \sim 0.1\, k_0$, $\Delta_{\parallel} \sim 1$ km, $W_a \sim 1$ kW, $h \sim 3$ km, $e_0 \sim 10^2$ kV/m, $c_s \sim 300$ m/s, we have: $\bar{\mathcal{E}} \sim 0.5$ mV/m, the frequency shift $\delta F \sim 0.03$ Hz, the frequency broadening $\sqrt{\Delta F^2} \sim 0.01$ Hz.

New experimental acoustic radiation equipment was developed at the Radiophysical Research Institute (NIRFI) in 1986-1987 to measure the radioacoustical sounding of the astmosphere in the band of sound frequencies 38-43 Hz. The setup was mounted in the form of a square array of nine radiating modules. The maximum of the antenna pattern is directed vertically upwards and the calculated pattern width is 42^0. The maximum power of the whole array is 400-450 W.

3.1.6 Studies of the Lower Ionosphere Using the Artificial Periodic Inhomogeneities

Principal investigator: Dr. Nikolai Goncharov (NIRFI).

Research group: Dr. V.V. Belikovich, Dr. E.A. Benediktov, Dr. N.P. Goncharov and Dr. A.V. Tolmacheva.

A research group from the Radiophysical Research Institute (Nizhny Novgorod, Russia) has been developing diagnostic methods which use ionospheric modification by high-power HF radio wave to investigate the earth's atmosphere and ionosphere. The methods are based upon application of the artificial periodic inhomogeneities (API) [115]. The inhomogeneities are created by a standing radio wave which occurs due to interference of a high-power decametre radio wave beamed vertically upwards and its reflection in the ionosphere. At heights below approximately 120 km, the primary cause of an artificial inhomogeneity generation is differential heating of electrons by the standing wave field. The differential heating in the upper D and lower E region leads to diffusive redistribution of plasma and at heights 55-75 km causes generation of the artificial inhomogeneities in the electron density through electron temperature dependence of the electron to the molecular oxygen attachment rate.

The API can be observed using Bragg backscatter of a pulsed diagnostic radio wave. By studying characteristics of the scatter echoes and their variations with time, we can derive or estimate the following parameters of the atmosphere and ionosphere.

- Electron density profiles N(h)
- Ambipolar diffusion coefficient D_a and parameters (it depends on neutral temperature and neutral density) in the E-region.
- Estimates of negative ion chemistry parameters in the lower D-region.
- Vertical velocities in the atmosphere at D- and E-region heights.

All these parameters can be obtained with time resolution sufficient to study short-term variations in the atmoshpere.

These techniques were successfully tested, but have not been widely used, except for some limited measurements. The research group is interested in further development of the new methods and in putting them into operation on a regular basis.

The EISCAT Scientific Association is interested in the application of the new methods.

3.1.7 Remote Diagnostics of Parameters of Artificial Inhomogeneities

Principal investigator: Prof. Yuri Ignat'ev

Artificial ionospheric irregularities occur under the action of powerful HF radio emissions on the ionospheric plasma. The method of reciprocal-oblique sounding of an artificially disturbed region of the ionosphere is based on the reception of

back scattered signals and permits definition of the basic parameters of the region and its irregular structure.
Investigation of the characteristics of back scattered signals, using the method of statistical analysis, makes it possible to define such parameters of artificial irregularities of the ionospheric plasma as longitudinal $\ell_{\parallel}$ and transverse $\ell_{\perp}$ scales (relative to the geomagnetic field H_0), the value of the relative electron density $\Delta N/_N$, and the spectrum of irregularity scales. The space-dispersed reception of back scattered signals makes it possible to study the motion of the diffraction picture of the field on the earth's surface and to define the horizontal motions $\vec{v}$ of plasma at altitudes of the disturbed region.

The first experiments by the method of reciprocal-oblique sounding of an artificially disturbed region at frequencies 2...6 MHz were carried out at the NIRFI facility "Sura" [116,117].

Besides the velocities of plasma motion, the given method (with further corrections) allows for the definition of such characteristics of the regular ionosphere as electron temperature T_e, effective frequency of collisions ν_{eff} and electron N_e density at altitudes of back-scattered signal observation. Changing the working frequency of the facility for the ionosphere modification can form artificially disturbed regions at different altitudes and define the height profiles of the basic ionospheric parameters ν(h), T_e(h), ν_{eff} (h), N(h). On the basis of experimental and theoretical investigations, it is suggested that recomendations be developed for the organization of parameter monitoring of the regular ionosphere, as well as control service for the artificially heating the atmosphere and ionosphere in order to take ecological problems into account.

3.1.8 Fractal Characteristics of the Signals Propagating Through the Ionosphere

Principal investigator: Dr. Mikhail Tsimring (NIRFI).

The signal from earth and space sources that travels through the ionosphere, has a noise-like, complicated character. SEE (Stimulated Electromagnetic Emission), caused by the effects of powerful radiowaves on the ionosphere, could be considered as an example of such a signal. Selection of quasi-noise signals by traditional methods of spectral analysis may be impossible in some cases. The authors of this project offer a new approach: fractal analysis for the solution of this problem. Fractal analysis can define the number of degrees of freedom for the signal and the spectral range where they are concentrated [118-120].

This approach makes it possible to detect streamlined signal images on the background of the noise of the ionospheric communication chanel.

3.1.9 Effects of Powerful Oblique and Vertical Radiation on The Ionosphere

Principal investigator: Dr. Gennady Bochkarev (IZMIRAN).

GOAL: The study of the physical nature and the mechanism of decameter radio wave propagation under conditions of antropogenic impact on the ionospheric plasma of powerful radiowaves.

The basis of the investigations: First results were obtained at the IZMIRAN in 1977-1982 years [121, 122]. This reseach was recently continued by Bochkarev and several American groups

[123-125]. The difference between the oblique versus vertical sounding is the usage of the operating frequencies which are significantly greater than those of plasma. This situation complicates the application of resonance theory to describe the effects on the ionosphere of big flows of electromagnetic energy.

Area of application. This work will make it possible to build a model which fully describes physical processes in the ionosphere. This model, in turn, will facilitate in the design of a new generation of radio communication equipment. This model will also help to explain atmosphere-ionospheric interconnections and their effects on the terrestrial ecology.

3.1.10 Investigation of the Influence of Artificial Plasma Inhomogeneities on Radiation of Whistler Waves Under the Earth's Ionospheric Conditions

Principal Investigator: Prof. Igor G. Kondrat'ev, the University of Nizhny Novgorod.

Research Group: Professor I. G. Kondrat'ev, University of Nizhny Novgorod A.V. Kudrin, assistant at the University of Nizhny; Novgorod T. M. Zaboronkova, leading research scientist at the Radiophysical Research Institute; Nizhny Novgorod, and A. I. Smirnov; senior research scientist at the Institute of Applied Physics, Nizhny Novgorod.

GOAL:
The main purpose of the investigation is to theoretically prove the possibility of using the artificial plasma inhomogeneities to increase the radiation of whistler waves in the ionosphere. Some preliminary results [126, 127] demonstrate the feasibility of using such plasma inhomogeneities for the increase of

radiating power of given sources in comparison with the case of homogeneous background plasma [128] in the whistler frequency range.

The Project is expected:

1. to investigate in detail the influence of artificial plasma inhomogeneities surrounded by the homogeneous background plasma and stretched along the external magnetic field on the radiation of whistler waves;
2. to demonstrate that artificial plasma inhomogeneities with enhanced (relatively background) plasma density can lead to the considerable increase of a radiation power of loop antennas in comparison with the case of homogeneous background plasma;
3. To perform for the earth's ionosphere conditions the concrete estimates of the practically achievable gain in a radiation resistance value of loop antennas, including the estimates of possibilities of the self-consistent nonlinear formation of required inhomogeneities, and to present general recommendations;
4. To fulfill estimates and present recommendations for the laboratory simulation of corresponding phenomena.

The project's conclusions can be used in practically all the areas where applications of whistler waves are possible. These areas include, in particular, the excitation of the ionospheric waveguide and the waveguide "Earth - ionosphere" for the development of various communications channels (including global ones), the diagnostics of the ionosphere and magnetosphere of the earth, and the deliberate influence on the geophysical situation.

The following schematic design (Fig. 1) indicates the institutes researching the effects of high power radio waves on the inosphere. Some of these institutes have been visited by the authors of this

review (unbroken line); others are known from the literature search (broken line).

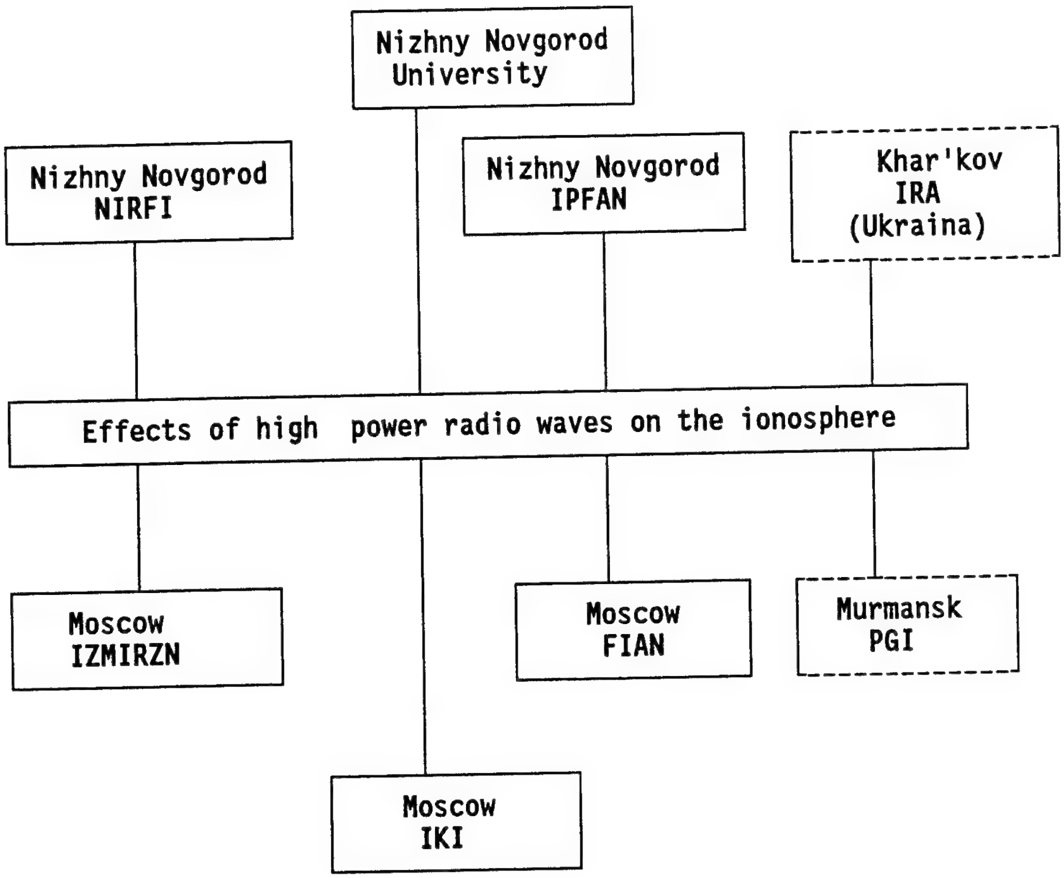


Fig. 1

3.2 Theoretical Treatment of the Problem of Radio Wave Propagation in the Ionosphere

The high theoretical level of many research groups of Russian scientists involved in ionospheric investigations allows for the possibility for further development of the theory of E/M wave propagation and scattering in plasma.

The institutes where this research takes place, and which have the most prominent theoreticians and theoretical groups in the country, are shown in Fig. 2.

As indicated by the literature search, the development of theoretical methods for ionospheric research, has been presented in 2.2 of this report. The problems, which have been discussed at the meetings at Russian institutes and which will be the subjects of future theoretical investigations, are presented below.

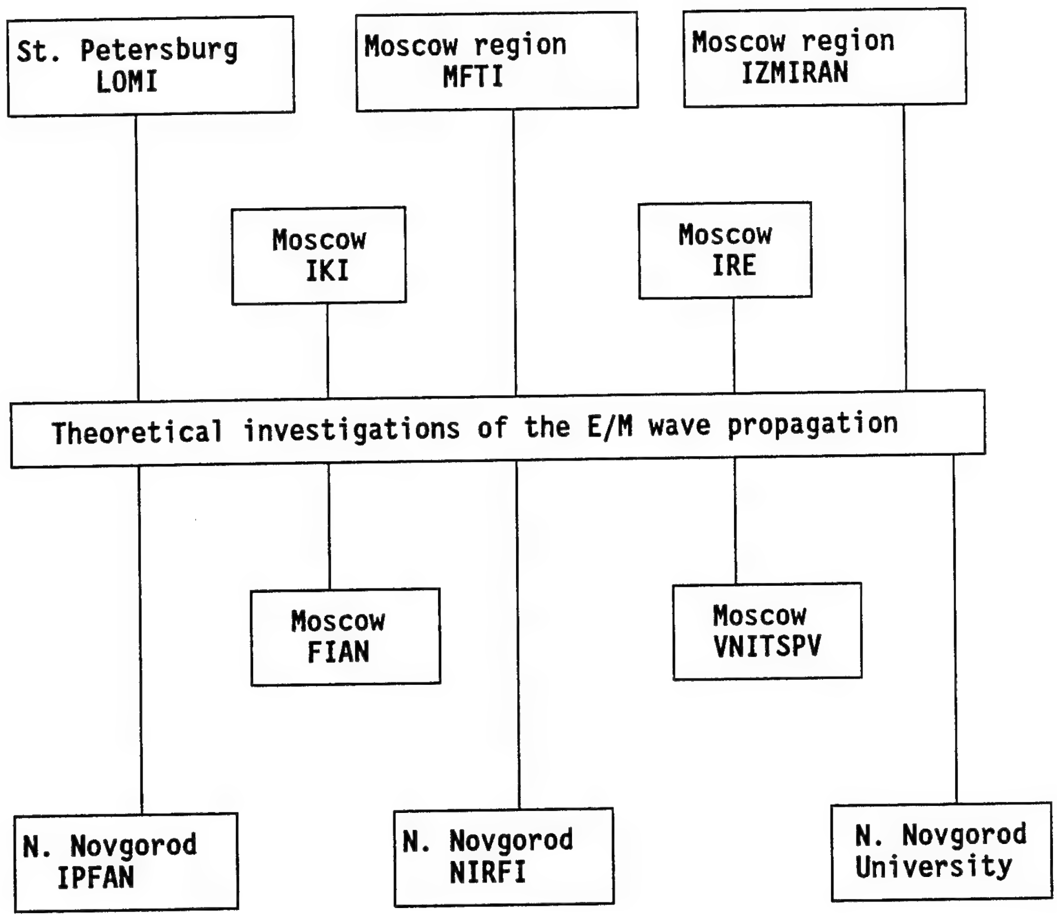

St. Petersburg
LOMI
Moscow region
MFTI
Moscow region
IZMIRAN
Moscow
IKI
Moscow
IRE
Theoretical investigations of the E/M wave propagation
Moscow
FIAN
Moscow
VNITSPV
N. Novgorod
IPFAN
N. Novgorod
NIRFI
N. Novgorod
University

Fig. 2

3.2.1 Propagation and Scattering of Electromagntic Waves in Random Atmosphere and Ionosphere

Principal investigators: Prof. M. Kalinin (VNITSPV, Moscow) and Prof. Yu. Barabanenkov (IRE, Moscow).
Number of participants: 6.

In dense discrete random media the mean distances between scatterers are the same as their typical sizes. Therefore, the spatial correlations between scatterers, generally of all orders, become considerable and cause various cooperative effects in problems of wave propagation and scattering [129, 130]. This situation occurs, for example, in a problem of atmospheric and ionospheric sounding when electromagnetic waves propagate through dust, smog, clouds, fog, ionospheric irregularities, etc. This study proposes to investigate the wave propagation and scattering in dense discrete random media taking into account the above effects.

3.2.2 Asymptopic Methods for the Problems of Wave Propagation

The Laboratory of Mathematical problems in Geophysics, headed by Professor Vasily Babich at the St. Petersburg branch of the Steklov Mathematical Institute (LOMI) of the Russian Academy of Sciences, specializes, primarily, in the development of the asymptotic approach for the theory of wave-like processes, including the geometrical theory of surface waves and wave fields in the vicinity of caustics [6, 37, 54-56].

Research group: Professor V. Babich, Professor M. Popov, Dr. N. Kirpichnikova, Dr. V. Filippov, and Dr. Z. Yanson.

In collaboration with the research group of Professor. G. Petrashen' of the University of St. Petersburg, Babich's group developed the qualitative and quantitative analysis of stratified elastic media on the basis of analytical solutions.

3.2.3 Gaussian Beams Summation Method and its Application for Computations of High Frequency Wave Fields in Electromagnetic Media

Principal investigator: Professor M. M. Popov.
Research group: Dr. A. P. Katchalov and Dr. N. Y. Kirpichnikova.

Gaussian beams summation methods have been created, developed and tested in the St. Petersburg branch of the Mathematical Institute during the years 1980-1987, as indicated in papers written by M. M. Popov, A. P. Katchalov and N. Y. Kirpichnikova, on acoustic and elastic wave propagation [6, 55]. The main advantage of these methods, as compared with the ray method, is the possibility to investigate and compute wave fields in the vicinity of caustics of arbitrary structures.

The researchers suggest the development of the Gaussian beams summation method for electromagnetic wave propagation both for frequency and time domains (wave packet propagation), including processes of electromagnetic wave propagation in the ionosphere. The main goal is to create a system of programs for computations of high frequency wave fields in electromagnetic media which would be suitable for the investigation of the upper atmosphere, the location of moving objects, etc.

3.2.4 Shortwave Scattering of a Plane Wave on Smooth Periodic Boundaries and Echelettes

Research group: Professor M. Popov, Dr. V. Zalipaev (LOMI).

In the papers by Popov and Zalipaev [131, 132] a shortwave asymptotic approach has been developed for the scattering problem of a plane wave on a smooth periodic boundary, based on a summation of multiple diffracted fields.

This approach leads to a complete asymptotic description of the diffracted field in a range of parameters when direct numerical methods pose difficulties.

Based on these results, the researchers suggest developing a shortwave theory of radiowave propagation near the ocean surface (radio location near waved surfaces) and an asymptotic theory of echelettes to be used for astronomical purposes.

The researchers expect to obtain approximate formulas for the wave field which would be suitable for detailing the physical analysis of corresponding wave propagation phenomena.

3.2.5 Application of Integral Transformation Methods for the Acoustic Investigation of an Oil Borehole

Principal investigators: Professor P. V. Krauklis, Professor L. A. Molotkov (LOMI).

They propose to study elastic waves exciting acoustic sources in a cased borehole for different contact conditions between casing and formation. In some conditions, unusual waves (Kr- wave) arise in this system. These waves can be used for the technical control of the oil borehole. To investigate Kr-waves we propose the integral transformation methods which have been developed in our monographs [133].

3.2.6 The Investigation of Wave Propagation in Cracked Media

Principal investigators: Professor L. A. Molotkov, Professor P. V. Krauklis (LOMI).
New models of cracked media have been obtained recently by using the procedure of averaging layered elastic-liquid media and elastic media

with slide contacts on boundaries [133, 134]. In the case of periodic elastic-liquid layers, the effective model is a two-phase medium described by new equations. Lamb's problem for cracked halfspace has been solved. The results of these investigations are in agreement with the experiments of Schoenberg, Plona and Winkler.

The investigations of wave propagation in cracked media will be continued in 3 directions:

1. Generalization of the theory for the cracks of finite length.
2. Investigation of wave fields in cracked thin layers.
3. Investigation of wave fields in cracked media which is a model for oil reservoir rock.

3.2.7 The Institute of Applied Physics (IPFAN) of the Russian Academy of Sciences at Nizhny Novgorod includes several theoretical groups which carry out high level research in the field of radio wave propagation in the ionosphere. The following projects are in progress:

Radio Wave Beams in the Ionosphere

Principal investigator: Dr. German V. Permitin, Senior Researcher, IPFAN.
Number of participants: 3.

The project is aimed at the development of a computer program for fast calculations of wave beam structures in smoothly inhomogeneous media like the earth's ionosphere, as well as a graphic presentation of the results on a PC monitor.

The calculation method is based on a presentation of the wave field as superposition of virtual wave objects, whose parameters can be obtained by integrating a system of ordinary differential equations along the base ray [135, 136].

The investigators should take into consideration the effects of nonlocal thermal nonlinearity leading to a shift of the propagation path and beam self-focusing. Tentative research studies demonstrated the possibility of such a program.

Radio Ray Aiming in the Ionoshpere

Principal investigator: Dr. Alexandra Sharova, Head of Laboratory of Information Systems, IPFAN.
Number of participants: 2.

This project considers the development of an interactive program for aiming rays of various types at a given region within the Earth-ionosphere waveguide. The program is based on Newton's algorithm for solving transcendental equations with some modifications that expand attractive zones and improve a convergence of the iterative procedure. The tentative variant of the program demonstrated efficiency and stability of the proposed aiming mechanism.

Quasi-Optics of Smoothly Inhomogeneous Magneto-Active Media

Principal investigator: Dr. Alexander I. Smirnov, Senior Researcher.
Number of participants: 3.

The project considers the generalization of the diffraction theory of aberrations for smoothly inhomogeneous anisotropic and gyrotropic media like the Earth's iohosphere. Such a generalization was performed for isotropic media [138, 139]. The results obtained are expected to be published in 1993.

3.2.8 Interaction of Wave Beams with Plasma

One of the most outstanding scientists in the field of plasma physics is Prof. Nikolai Erokhin. He has a strong group at the Space Research Institute (IKI) of the Russian Academy of Sciences.

The main research directions of this group are listed below:

1. Linear wave transformation in inhomogeneous plasma (wave transformation on gradients of plasma density and geomagnetic field).
   Applications: plasma heating due to the conversion of radiation from ground based transmitters into fast relaxing plasma wave [140-142].
2. Nonlinear effects during E/M wave propagation in inhomogeneous plasma: self-focusing beams of E/M waves, filamentation strong E/M waves, a generation of high harmonics, instability, nonlinear waveguides [141, 142].
   Applications: long-distance propagation of E/M radiation. Concentration of radiation in small volumes, splitting of wide wave beams, for example, EHF radiation or solar space electro-stations [143].

3 Acceleration of charged particles by high power E/M waves in inhomogeneous plasma [141, 142]. Standard mechanism of particles in near-Earth space and modulation of flows of these particles.

4. Clarification of wave barriers (penetration of E/M wave through opacity layers of plasma) with the help of resonant charged particles [144]. Waves transmit their energy to particles which penetrate through wave barriers and reproduce an initial signal beyond them.
   Applications: radio communication, nonlocal transmission of disturbances.

5. E/M wave excitation by small antenna. Excitation of waves with strongly retardation in ionospheric plasma.
6. Generation of artificially ionized layers in the upper atmosphere.
7. Auroral kilometric radiation.
8. Transport through the ionosphere of EHF radiation from solar space electro-stations [143].
9. Reley-Taylor instability of night equatorial ionosphere [146] (generation of plasma bubbles, their arising to the surface, generation holes in F-layer with a horizontal size $\sim$ 50 km, and vertical size $\sim$ 200-500 km).
10. Radio wave monitoring of the state of lower ionosphere and litosphere-ionosphere interaction.
11. Movement and heating of particles in stochastic magnetic fields [147, 148].
12. Interaction of EMF waves with biological objects.

3.2.9 Wave Catastrophy Functions

A highly advanced theoretical group (Professor D. Lukin, Dr. A. Kryukovsky, Dr. E. Palkin et al) at the Moscow Institute of Physics and Technology (MFTI), Department of Antennas and Propagation, is developing new techniques for the calculation of fast oscillating integrals. The asymptotics of these integrals are presented with the help of special functions of wave catastrophes. The computational algorithms for the calculation of these functions are developed by the scientists of this group.

This approach could be used for solving a large number of problems in the field of wave propagation, scattering and diffraction of waves in inhomogeneous medium [47, 149, 150]. For example, they examined the problem of pulse radiation of the limited apertures having smooth edges or edges with corner points placed in inhomogeneous plasma [149] as well as diffraction of electromagnetic waves by metallic screens [150].

3.2.10 Radio Wave Passage Through a Turbulent Plasma Layer

Professor Vladimdir Glagolevsky of the St. Petersburg Institute for Aviation Instrument Manufacture (LIAP) proposes the following theoretical research concerning flat layer, flat incident wave and normal wave incidence. The result of the solution of this problem is the relationship between the power spectrum of the passed wave field and the statistical characteristics of the turbulent pulsation process of the electron concentration in the layer. For the temporarilly stationary and spatially statistically uniform process, the research is expected to end with an applied formula. This formula will determine the power signal to noise ratio at the end of the layer. This ratio depends on the layer's thickness, incident wave frequency, and the coefficient describing the wave passage through an undisturbed layer, as well as the intensity and turbulent scale of the electron concentration.
The results can be applied to the spectrum and signal-to-noise ratio estimation for a RF signal passage through plasma shells around real objects moving in the air.

3.2.11 The Institute of Terrestrial Magnetism, the Ionosphere and Radio Wave Propagation (IZMIRAN) of the Russian Academy of Sciences includes several departments which carry out the research on the ionosphere.

The Department of Ionospheric Radio Wave Propagation headed by Professor Yu. Cherkashin is developing research mainly in the following directions:

Nonlinear Effects In Wave Beam Propagation Through the Ionosphere

Principal investigators: Professor I. Molotkov and Professor Yu. Cherkashin (IZMIRAN, Moscow region, Troitsk).

GOAL: to obtain analytical expressions for self-impact and impact on the medium of wave packets. These wave packets are described by Helmholtz's cubic-nonlinear equation.

The basis of the investigations: Molotkov and Cherkashin, (1992, personal communication), recently found an asymptotic solution of Helmholtz's equation at $\omega \to \infty$ and the conditions in which the solution is concentrated around a trajectory of the central ray of the beam.

This approach is applied to calculate of the effects of self-impact and impact on probing wave beams in the ionosphere.

Specifically, they found:

1. A significant deviation up from the axis line of a powerful wave beam when the source is on the Earth.
2. The propagation of a powerful beam results in additional split of the medium. If the intensity of the beam is high enough, then a controllable waveguide and anti-waveguide appear in the ionosphere.
3. The trajectory of low intensity of probing beam passes above the trajectory of a powerful beam when the carrying frequencies of the beams are equal.

Area of application. This approach allows a numerical estimation of the values of all the effects mentioned above. The current power of antenna fields is relevant to the effects described in this research.

3.2.12 New Method of Wave Field Calculation in an Inhomogeneous Medium

Principal investigators: Professor Cherkashin and Dr. Eremenko (IZMIRAN).

This method is a generalization of Huygens' principle together with geometrical optics of an inhomogeneous medium when $H \gg \lambda$, where H is the scale of medium variations and λ is wavelength.

The structure of the solution is presented as follows:

1. Initial wave field data are presented as a superposition of tightly localized wave packets.
2. The trajectory equations and transfer equations are written as a system of simple differential equations along the trajectories themselves. Under these conditions the transfer equation of each packet does not have any singularities, neither in focuses nor in caustics.
3. The superposition of such localized wave packets produces the asymptotic solution of Helmholtz's equation.

The main task is to optimize the width of the wave packets. The author has provided a solution of several scalar problems. This method could be extended to cases of diffraction from bodies of complex shape in inhomogeneous media.

3.2.13 Parabolic Equation Modifications and Narrow Beams of Radio Waves

Principal investigator: Dr. Alexei Popov.
Research group: 4 researchers.

This group is solving the problems that require significant modifications of the parabolic equation (PE).

1. The E/M wave propagation in inhomogeneous dielectric films of variable thickness is analyzed. Solving this problem requires a search for the asymptotic solution of the full system of Maxwell's equations. Under certain conditions a division of TE and TM modes occurs. Consequently, the problem is reduced to the integration of a system of horizontal rays.

2. The model considered is of irregular waveguide with a boundary containing quasi-periodic inhomogeneities on the background of its smooth global evolution. A method of two scale expansions is used to solve this problem for long distances.
3. ELF radio wave propagation in the Earth-ionosphere waveguide is considered. This waveguide is characterized by a strongly nonuniform profile of complex dielectric permeability. To describe this situation the authors use hybrid PE, taking into account the refraction in the reflection region as well as diffraction along all the waveguides [151].
4. Development of algorithms of adaptive radiocommunication by narrow beams of radiowaves is investigated. The evolution of Gaussian beams in the nonuniform Earth-ionoshpere waveguide was considered first in [152]. Future research is planned to extend these results for the practical realization of new principles of radio communication, providing high energy concentration in the receiving point.

3.2.14 Investigation of interference field on multi-element antennae lattice

Principal investigators: Dr. A.Popov, Dr. A.Karpenko.

Popov et al. worked out the following system: a multi-element antennae system, multi-channel radio receivers, high accuracy standards of time and frequency, a registrator based on the IBM PC and signal processor TMS320C25. This complex is used to analyze radio signals passed through the inhomogeneous nonstationary ionosphere.

In the future, Popov et al. plan to work out a correctable empirical model of the ionosphere along a given direction (azimuth). They also plan to develop optimal algorithms of space-time signal processing.

3.3 Ionosphere modelling and forecasting

In Russia many groups of scientists from different institutes are involved in research on the problems of ionosphere modelling and forecasting. We have visited some of them, as shown in the Fig. 1 (unbroken line).

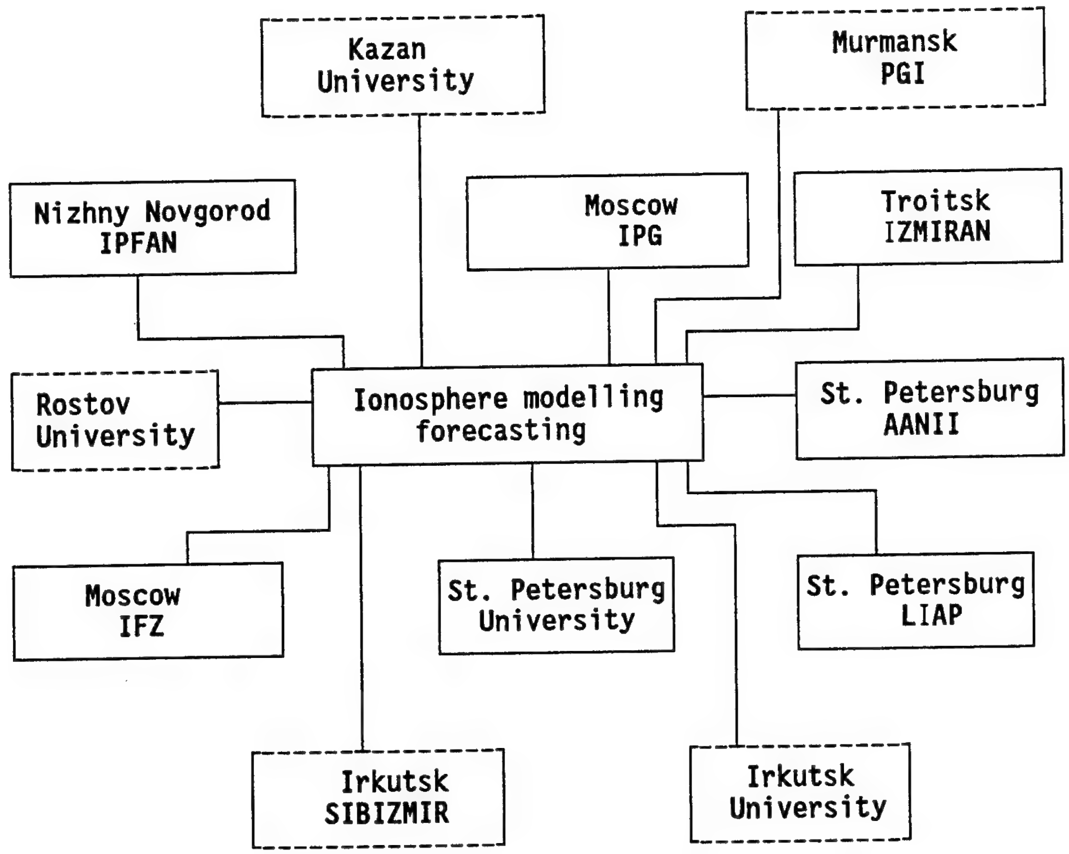


Fig. 1

Institutes where research groups are working in the same field, but which we did not visit, are presented in Fig. 1 by broken lines. We learned about these institutes in the literature search [77-100].

The status of the problem is described in part 2.7 of the present report. In this report we present the proposals for carrying out the research in the field of ionospheric modelling and forecasting.

3.3.1 Dr. Mikhailov, the Head of the Laboratory of Ionospheric Modelling at the Institute of Applied Geophysics (IPG) in Moscow, proposes the following elaborations:

- A new effective ionospheric index of solar activity for modelling and long-term (1-12 months) forecasting of planetary distribution of monthly medians of f_0 F_2 for solving the problems of HF communication.

- An ionospheric database formed by the world network of ionospheric sounding stations for several cycles of solar activitiy.

- New methods for long-term (1-12 months) and short-term (1-24 hours) ionospheric forecasting.

- Application of a database for a world network of ionosphere sounding stations, satellite data observations and theoretical models to study:
  a) physics of positive and negative disturbances in the F2-region of the ionosphere
  b) physics of longitudinal variations of parameters of the F2-region during geomagnetic storms
  c) connection between disturbances in the termosphere and F2 ionospheric region

- SPARC - System of Prediction and Analysis of Radio Communication.

SPARC is designed to provide worldwide HF communication diagnostics and forecasts. It is based on the IPG experience in exploring, modelling and predicting ionosphere, archiving and processing data of current observations from our own ionosondes network. This network includes about 20 ground-based stations, scientific satellites and data coming from other Warning Centers. It allows us to produce long-term forecasts for a monthly median ionosphere. Providing current ionospheric data are available in the area of radio circuit control points, short-term forecasts up to 24 hours in advance could be performed. SPARC comprises a high-latitude ionosphere model for the northern hemisphere and may be used to support HF communication in that area. The 12-month running mean sunspot number R12 is the only geophysical parameter which can be used to produce a monthly median HF forecast. To support real-time communication, current data on critical frequencies of F2-layer (foF2) are required in the area of interest, and 3-hour geomagnetic K-indices are called for HF predictions in a high-latitude region. These parameters observed and predicted may be obtained from Moscow's Main Warning Center at IPG or from other World Regional Warning Centers.

As a result of complex but very fast calculations, SPARC recommends optimal frequencies (fig. 2) to maintain HF communication with a desired service quality.

SPARC produces Median and Decile Maximum and Lowest Usable and Operative Frequencies (MUF, FOT, HPF and MOF, LUF), Take-Off Angles, Propagation Modes, Field Strength, Signal-to-Noise ratio and Service Reliability at receiver site. It takes only 20 sec at AT-286/287 (16 MHz) to get daily variations of all these parameters for any radiocircuit.

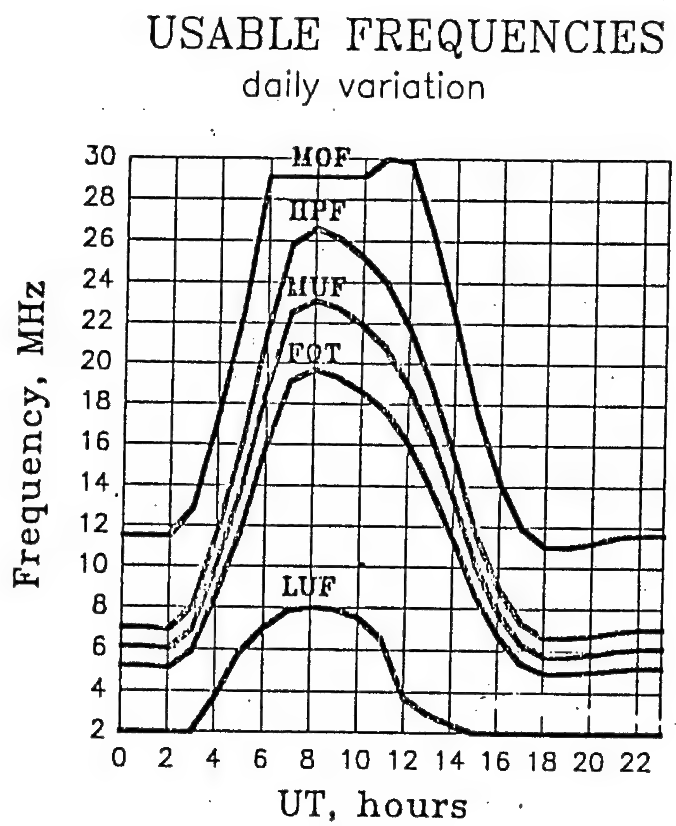


Fig. 2. Daily variations of frequencies applied to HF communication for radiocircuit Moscow-AlmaAta on Oct. 1, 1990 (see TERMINOLOGY for terms regarding frequencies definition). Working frequencies should fall into between LUF and MOF, Optimal Traffic Frequency (FOT) is usually recommended one. Provided that you have a color monitor various curves will be of different colors.[193].

Computed results can be analyzed as a function of UT (daily variation for selected frequencies) or frequency from 2 to 30 MHz (frequency variation for selected UT) in tabular form or in a graphics presentation (fig.3,4). SPARC represents automatically only that area of calculated parameters where communication is possible for required service quality. A hard copy of any computed result is available.

Very user-friendly interface, which includes context sensitive help, a comfortable and easy menu system, a simple system designed for various types of hardware along with the powerful set of forecasted parameters and their analysis tools, make SPARC very useful.

TERMINOLOGY

MUF — highest frequency at which a radiowave can propagate between given terminals 50 percent of the time by ionospheric refraction alone.

FOT the same as MUF but with efficient ionopsheric support 90 percent of the time.

HPF the same as MUF but with efficient ionospheric support 10 percent of the time.

LUF frequency below which signal-to-noise ratio is unacceptable.

MOF frequency above which signal-to-noise ratio is unacceptable.

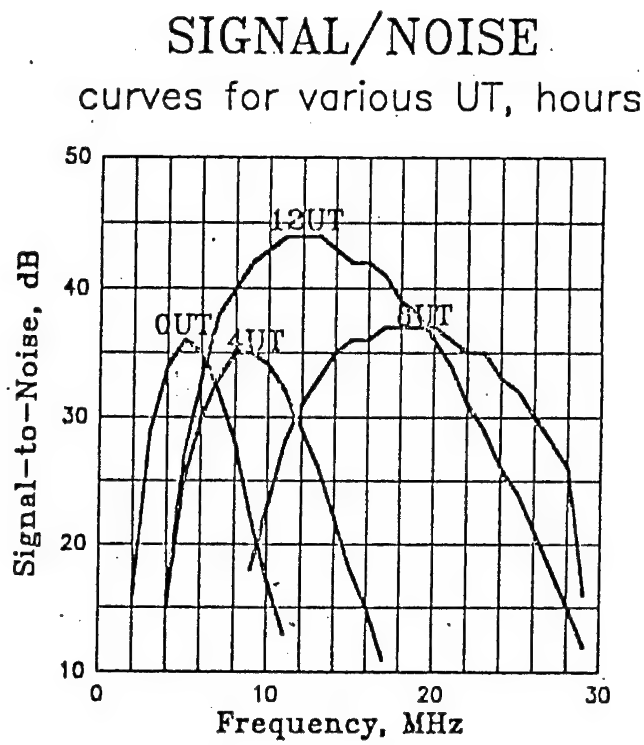


Fig.3. Signal-to-Noise ratio vs working frequency for 0, 4, 8, 12 UT for radiocircuit Moscow-AlmaAta on Oct.1, 1990. Only those segments of curves are shown that exceed required signal-to-noise ratio (equal to 10 dB in this case). The chart shows if you want to choose for communication a time period with a highest signal-to-noise ratio at frequency 11 MHz, for example, you may consider 12 UT as the best choice. There is also a range of frequencies near 9-10 MHz which enables you to operate the radiocircuit all round the clock. Provided that you have a color monitor various curves will be of different colors to make them distinguished easily.[193].

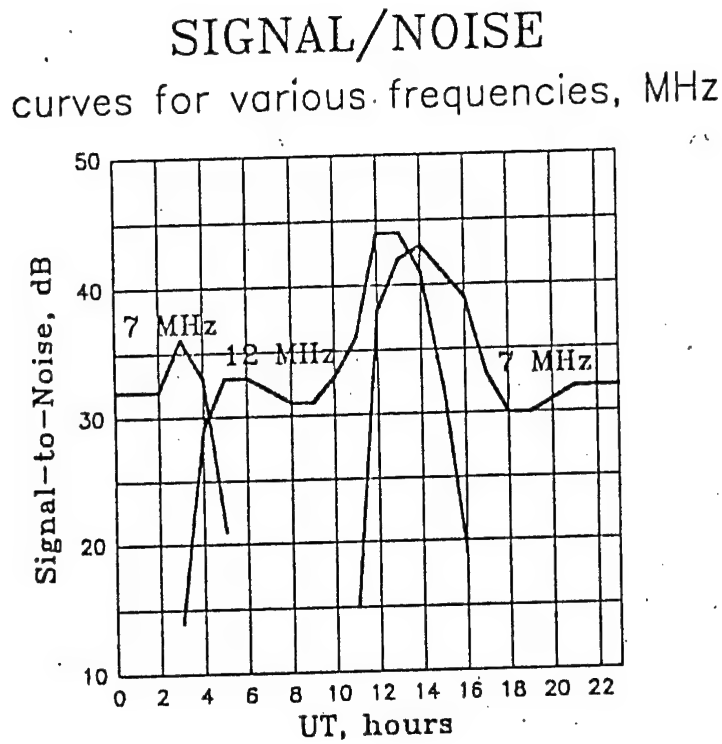


Fig.4. Signal-to-Noise ratio vs UT for frequencies 7 and 12 MHz for radiocircuit Moscow-AlmaAta on Oct.1, 1990. Only those segments of curves are shown that exceed required signal-to-noise ratio (equal to 10 dB in this case). It may be seen, for example, that these frequencies may be used as a two-frequency complement to assure twenty-four hour services operation: at 7 MHz from 0 to 4 UT, at 12 MHz from 4 to 14 UT and at 7 MHz from 14 to 24 UT. You may also plan optimum communication time at fixed frequencies using such graphics. Provided that you have a color monitor various curves will be of different colors to discern them easily[193].

SPARC FEATURES

* World-wide long-term as well as short-term HF communication
* working frequencies predictions
* Field strength, radio noise and circuit reliability calculations
* Adapting background model ionosphere to current ionospheric data
* Updated high-latitude ionosphere
* Storage of all pertinent information in highly efficient tabular form databases
* Easy and comfortable menu system with context sensitive on screen help
* Detailed tutorial
* Color graphics presentation of calculated parameters
* Built-in analysis tools that easily produce expert conclusions concerning HF communication

SYSTEM REQUIREMENTS

* IBM family of personal computers, all 100% compatible
* 640K of RAM
* Hard disk
* DOS 2.0 or higher
* Compatible CGA, EGA, VGA or Hercules with adapter

Optional equipment:

* Compatible dot matrix, letter quality, laser printer or plotter
* EMS or EEMS board or other expanded memory adapter for faster performance
* Math coprocessor for faster calculations

3.3.2 Extended Forecast of HF Communication Possibility in Quiet and Disturbed Ionoshpere of Middle and High Latitudes

Professor Mishin, Head of the Department at IZMIRAN, has developed a different approach for ionospheric forecasting.

Existing methods of HF communication forecasting through the ionosphere deal mainly with MUF or frequency ranges of different modes of propagations. Professor Mishin expects to develop a forecasting technique (and corresponding computer programs) for a more extended representation of frequency ranges, group delays, and mode structures of signals, and estimate the optimal frequency range and other parameters for digital communication links.

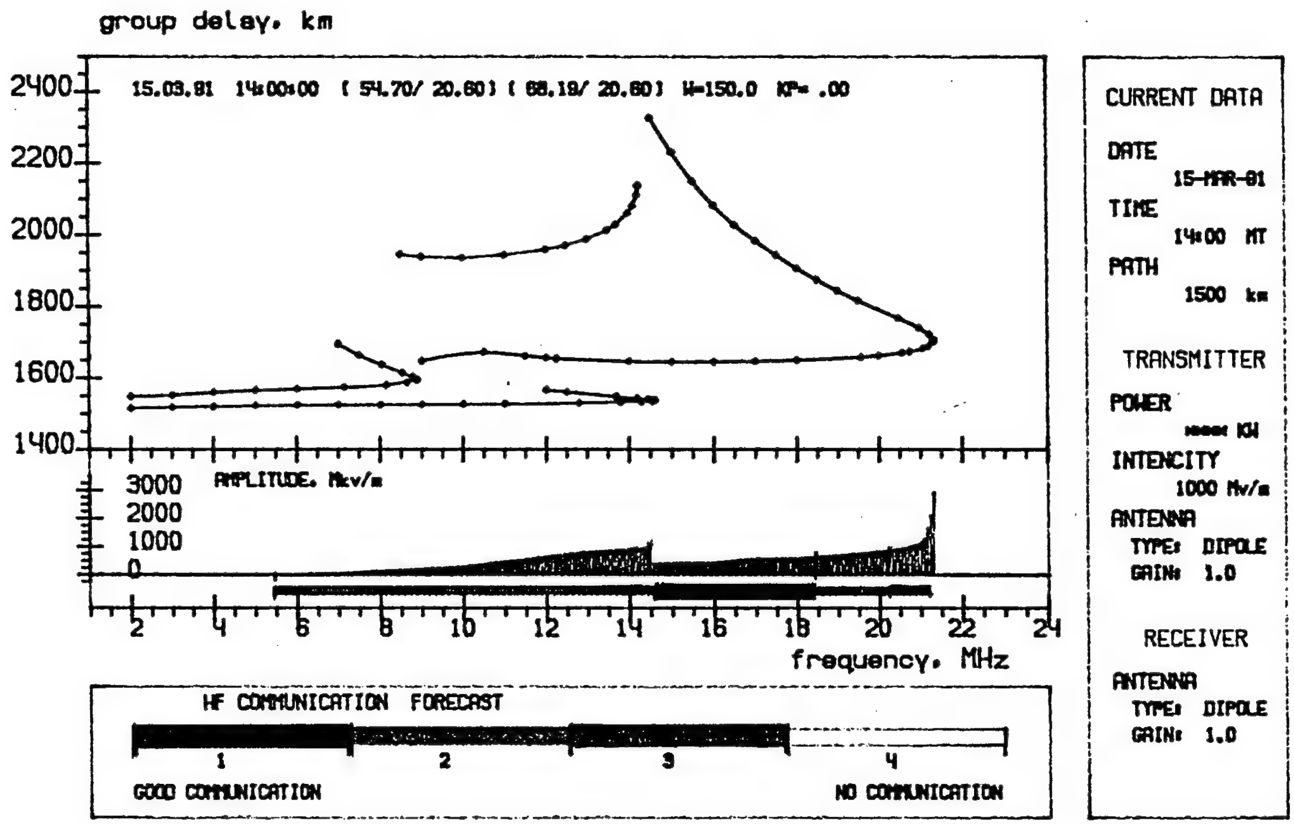
This techique includes:

i) ionospheric models appropriate for quiet and disturbed conditions, capable of considering the following kinds of disturbances: ionospheric storms, inospheric effects of magnetospheric substorms and disturbances connected with solar flashes (SID, PCA, AA);

ii) a possibility of correcting the ionospheric models on current geophysical and radiosounding data;

iii) a synthesis of oblique sounding ionograms with a power-frequency function and an estimate of optimal frequency range for communication.

An example of the output information is presented in the figure below.



group delay, km
2400
2200
2000
1800
1600
1400
15.03.81 14:00:00 (54.70/ 20.60) (68.19/ 20.60) H=150.0 KP= .00
AMPLITUDE, Mkv/m
3000
2000
1000
0
2
4
6
8
10
12
14
16
18
20
22
24
frequency, MHz
HF COMMUNICATION FORECAST
1
2
3
4
GOOD COMMUNICATION
NO COMMUNICATION
CURRENT DATA
DATE
15-MAR-81
TIME
14:00 MT
PATH
1500 km
TRANSMITTER
POWER
KW
INTENCITY
1000 Mv/m
ANTENNA
TYPE: DIPOLE
GAIN: 1.0
RECEIVER
ANTENNA
TYPE: DIPOLE
GAIN: 1.0

3.3.3 Modelling of Equatorial Ionospheric F2-Region

Dr. Tatjana Leshinskaya, a senior researcher at the Department of Ionspheric Radio Wave Propagation at the IZMIRAN, in cooperation with Dr. Mikhailov (3.3.1), worked out the model of equatorial ionosphere [153-155]. This model is based on physical properties of low-latitude F2-layer. The model is suitable for describing the medium under quiet magnetic field conditions, for different seasons and levels of solar activity.

The distinctive features of this model include:

1. Use of one-dimensional equations.
2. System of basic aeronomical parameters which provide a high accuracy description of the medium .

When compared with the latest theoretical (two-dimensional) models of equatorial ionosphere by Nikitin-Kashenko and Anderson - Roble, this model proves superior in describing the F2-region under different heliogeophysical conditions.

Application of the Model:

1. Forecasting and calculation of low latitude radio paths.
2. Explanation of phenomena "bite-out" negative disturbances in the equatorical region, and possible explanation of the physical nature of equatorial splits.

3.3.4 Physics and Modelling of the Ionosphere

Dr. Tamara Soboleva, senior researcher at the department mentioned above, carried out the investigation on global modelling of the ionospheric E and F2 layers.

GOAL: to model the response of the ionosphere on the effect of interplanetary magnetic field (IMF).

The modelling is based on the measurements of electron density n_e both from a satellite at a height of 400 - 500 km, and from a network of ionosphere monitoring stations.

Expected results:

1. The global analytical model of median values of sporadic E-layer parameters:
   f_oE_s - critical frequency and $h_m E_s$ - the height of electron density maximum.
2. Analytical global model of variations: Δf_oE_s, Δh_mE_s as a result of IMF impact.
3. Analytical global model of variations foF2, hmF2 including auroral ionosphere, the main ionospheric trough, equatorial ionosphere, as well as longitudinal variations under changes of IMF.

3.3.5 The investigation of the dynamical and statistical effects in HF ionospheric reflection channel

Investigations in HF wave propagation are being carried out at the Institute for Aviation Instrument Manufacture in St. Petersburg (D. Blagoveshchenskii), in collaboration with the HF propagation group at St. Petersburg University (N. Zaalov, N. Zernov, A. Eliseyev) [156,157]. These scientific activities include:

1. development of the analytical techniques for the description of the fluctuating HF ionospheric reflection channel;
2. computer modelling of the dynamical and statistical effects in the HF ionospheric channel in geometrical optics approximation (ray tracing and pencil divergence) and for more complicated cases, when the diffraction effects are essential;

- experimental investigations of the dynamical and stastistical effects in the HF channel with natural and man-made disturbances by the Doppler method, including FFT in real time and statistical data processing; analysis of the oblique sounding data in the net of the radio paths;
- reconstruction of the electron density profiles for the HF ionospheric reflection channel based on oblique sounding data;
- ionospheric model correction based on the comparison between the calculated and measured oblique sounding data;
- the development of a semi-empirical model of the ionosphere describing the case of the quiet ionosphere as well as the ionosphere of storm conditions; the correction of the model in real time on the basis of the satellite and vertical sounding data.

.3.6 Prediction of Ionospheric Disturbances in a System of HF Radiopaths

rofessor Blagoveshchenskii is developing a method for predicting onospheric disturbances [86, 158-160].

he ionosphere disturbances include the sudden ionosphere disturbance SID), the polar cap absorption (PCA), auroral absorption (AA) and he ionosphere F-region disturbance. The radiopath system located at a eomagnetic latitude $60\text{-}65^{0}$ makes it possible to detect the SID ffects and to carry out the prediction of the auroral substorms and he global magnetic storms immediately related to PCA, AA and the -region disturbance. The basic method of the short-term (up to wo hours) prediction of magnetic ionosphere disturbance is 1) the vailability of the channel model in the form of accumulated data and) the channel diagnostics. The latter is the real-time acquisition of ata on the propagation medium by a) the envelope characteristics of he HF signal at the radio receiver output, b) the Doppler

measurements results, c) atmospheric radio noise or d) the results of the oblique sounding of ionosphere.

The objects of the studies, with the help of special radiopaths, are the ionospheric signatures of the cusp/cleft. Changing the sign of the IMF which precedes the onset of the magnetospheric substorms causes variations of the geomagnetic field and the ionosphere predominantly in the cusp region. It is expedient to collate the variations of the signal parameters at the paths traversing the cusp under quiet conditions and before a storm or substorm. The purpose of the collation is the development of a prediction method taking into account the character of the IMF components Bz, By, etc.

3.3.7 Wave Propagation in Inhomogeneous Medium

Professor Makarov, Head of the Department of Radiophysics at the University of St. Petersburg, organized the research groups to develop the following directions:

1. Methods of calculation and theory of the terrestrial wave propagation in the cases of inhomogeneous complicated propagation paths (including software).
2. Methods of calculation and theory of VLF wave propagation in inhomogeneous and anysotropic waveguide Earth-ionosphere (including software).

3.3.8 Experimental Modelling of Propagation and Interaction of Electromagnetic Waves in the Ionosphere

Principal investigator: Dr. V. A. Mironov, senior researcher.

The following investigations are proposed for the experimental set-up at the Institute of Applied Physics (IPFAN) of Nizhny Novgorod. This

experimental set-up makes it possible to model electrodynamic processes in the ionosphere under laboratory conditions [161-163]:

1) Transfer process in magnetized plasma (diffusion and thermodiffussion of charged particles by plasma exitation with an electromagnetic field).
2) Excitation of plasma turbulence in the zone of reflection (upper hybrid resonance) of an electromagnetic wave.
3) Stimulated electromagnetic emission (SEE) of plasma turbulence.

3.3.9 Models of Regular and Auroral Absorption in the Lower Ionosphere. Modelling of Ionospheric Effects of Substorms

Dr. Pavel Kishcha, senior researcher at the IZMIRAN, has developed the modelling of ionospheric absorption and ionospheric parameters during isolated and complicated substorms [164,165].
The George-Bradley absorption model has been improved for the middle latitudes and extended for the high latitudes on the basis of riometer data obtained for magnetically quiet conditions disregarding the aurural absorption. Such a model is called a "regular" absorption model. On the basis of riometer data, a model of the auroral absorption has been constructed as well. The model takes into account the degree of magnetic disturbance. An analytical description of the two models is carried out using high-order trigonometric functions.
The analytical model of regular and auroral asorption can be used for HF absorption predictions on radio paths of any length and orientation for various geophysical conditions.

Kishcha et al. propose a model of the ionosphere with large-scale disturbances during substorms. This model makes it possible to predict parametrs of the shaded ionosphere depending on the AE-index of magnetic activity for low, middle and auroral latitudes. Evaluations of the AE-index may be defined by current magnetic field data.

3.3.10 Modelling of the Size of the Polar cap and Magnetic Flux in the Magnetospheric Tail

One of the most urgent problems of magnetospheric physics is to find a set of key parameters which:

1. Gauge the magnitude of each of the principal magnetospheric processes.
2. Is readily available from routine and continuous ground-based and/or spacecraft measurements.
3. Would be used in the forecast practice as a diagnostic parameter [166-172].

One such key parameter is intensity of the current system of the magnetosphere tail. Changes in location and magnitude of the tail current system determine the transition process of the magnetosphere from a quiet state to a substorm and back [169]. The magnitude of tail currents depends on several factors. Perhaps one parameter which characterizes it best is the total magnetic flux in each of the tail lobes. That flux may be estimated from the observed magnetic field in the lobes. A much more direct estimate is based on the relation between this flux and the size of the polar cap. To our knowledge, no attempt has been made, so far, to experimentally establish a quantitative relationship between the polar cap radius (Rp) and the tail current magnitude. The problem can be formulated in an even broader way - namely, to find parameters (or indices) which could serve as a measure of temporal change of the tail electric current.

Dr. Oleg Troshichev, Head of the Department of the Arctic and Antarctic Research Institute of St. Petersburg, proposes to carry out the following research:

1. To create a database containing data on the size of the polar cap, by using the data on the Interplanetary Magnetic Field (IMF). It would be significant to compare the results obtained by different methods, such as measurements of precipitating

particles and auroral images from spacecraft DMSP.

2. To estimate the values of the potential drop $\Delta\Phi(t)$ across the Polar Cap and to study the relationship between potential drop and the size of the Polar Cap from obtained data on the Polar Cap size and the already available Polar Cap (PC) index values.
3. To calibrate the Polar Cap size against IMF parameters and geomagnetic activity in order to study the correlation between Rp with the Bz and By (Bx) IMF components and AE-index.
4. To calibrate the tail electric current magnitude against the Polar Cap size and the potential drop, to study the correlation of Rp(t) and $\Delta\Phi(t)$ with the measured tail magnetic field (ISEE data).
5. To develop a method for identifying the Polar Cap boundary during the periods with northward IMF, by using the data of the DMSP spacecraft on the precipitating ions. To develop an automated algorithm for identifying the Polar Cap boundary, suitable for any IMF conditions and any level of geomagnetic activity.
6. To carry out computations of Rp(t) and the Polar Cap drop values for the entire period 1984-1991.
7. To work out the algorithm of using Rp(t) index for the purpose of magnetosphere state monitoring.

Planned final results of the work:

1. An automatic algorithm to determine the Polar Cap boundary from satellite measurements.
2. A dataset on the polar cap size for the period 1984-1991.
3. Calibration of the magnetospheric magnetic field models against the parameters Rp.

3.3.11 Development of Earthquakes Prediction Methods by their Effects on Ionospheric and Space Plasma

Investigating of the Earth-ionosphere waveguide by super long waves (SLW) has been suggested to study of ionospheric sources related to seismic activity [173]. The "Omega" system of phase radio-navigation is used as the transmitting apparatus. The state of the lower ionosphere along the "transmitter-receiver" profile has been analysed on the basis of the amplitude and phase variations signal. The study of these variations was carried out on the Omsk-Liberia and Omsk-Reyunon seismo-active profiles. This investigation revealed night bay-like phase perturbations of the "Omega" system signal [173-175]. Statistical analysis showed the appearance of such phase perturbations for 10-20 days before the seismic events. This data was confirmed retrospectively for Spitack (Armenia, M=7.1, 1988) and Rudbar (Iran, M = 7.5, 1990) earthquakes.

The nature of night bay-like phase signal perturbations is connected with the formation of irregularity in the lower ionosphere. These ionospheric irregularities caused a splitting of the normal wave up several modes, which form the interference field in the receiving point. This hypothesis is confirmed by the experiments on the SLW oblique sounding of the ionsphere [174,175], when the sources of radiation were the transmitters of the pulse-phase radionavigation system "Loran-C".

Test predictions of earthquake time intervals have been made for several radio paths. Three earthquakes have taken place for predicted time periods: Rachinsk (Georgia, 29.04.91, M=7.1), its aftershock (15.06.91, M=6.2), and Rumania (2.12.91, M=5.7). In addition, seismic danger was announced from 9 up to 18.03.92 along the radio path Reyunion - Moscow. On the 13th of March a strong earthquake took place in East Turkey with M=6.8 (the distance between epicentre and profile is about 500 km).

In connection with these findings, two possible projects have been proposed by leading scientists at the Institute of Physics of the Earth.

Protection of nuclear power stations from earthquakes have been proposed by Professor M. Gokhberg through the development of a new nonseismic method. This method is effective in the zone near the object where seismic methods are not applicable.
The physical principles, methodological base and sensors to set up a similar protection system can be developed on the basis of an electromagnetic model earthquake focal zone.

Professor Strakhov, Professor Molchanov, et al. propose a system of the satellite electromagnetic (EM) plasma monitoring of the seismic activity.

The aim of this study is to develop and manufacture a global system for satellite EM plasma monitoring of seismic activity and to discover and investigate earthquake precursors.

The system proposes to:

1. record aboard the spacecraft near-Earth space disturbances that are generated as a result of seismic activity;
2. conduct fast analysis of seismogenic disturbances on board the spacecraft;
3. correlate analysis of results of simulataneous observations involving spacecraft and ground-based geophysical observatories;
4. channel the acquired data to the National Data Center for analysis.

The system proposes to record the following main parameters of space plasma:

1. electromagnetic emission above the epicenters of future earthquakes;
2. disturbances of electric and magnetic fields over the epicenter regions;
3. disturbances of the number density and temperature of plasma;
4. disturbances of high-energy geoactive partical fluxes;
5. intensity variations of the optical ionospheric emission above epicenter regions.

Scientific and technical basis of the project:

1. detection of earthquake-related effects in the ionospheric and space plasma during ground-based and satellite observations;
2. achievements of Russian space technology in the development of reliable long-term electromagnetically-clean automatic universal orbital stations permitting high-efficiency measurements in space plasma;
3. experience gained in the development and operation of high-sensitivity instruments to measure space plasma variations, already tested in several successful international project within the INTERCOSMOS Program.

BASIC DATA OF SCIENTIFIC PAYLOAD ON BOARD THE SPACECRAFT

Main Objectives:

1. analysis of earthquake indicators and develoment of a procedure to build the pattern of multifactor signature from simultaneous satellite and ground-based observations;
2. development of a procedure for computerized determination of the zone and aproximate evaluations of the time instants of an earthquake from spacecraft observations.

Specific features of the project:

1. a multiprocessor self-adaptive system for data acquisition and processing and for decision making;
2. electromagnetic cleanliness;
3. ground-based monitoring (simultaneous observations on geophysical test sites).

Main requirements for the satellite:

Orbit	CIRCULAR 600 km
Inclination	$60 - 81^{0}$
Mass of payload	<350 kg
Power consumption	<235 W (diurnal)
Accuracy of attitude	$< 1^{0}$ for three axes

Planning

The experiment is expected to be implemented in 1993-1997 on board the METEOR-3 satellite, in collaboration with French scientists.

3.4 Ionospheric data processing, experiments and other projects

This chapter deals wih projects on ionospheric data processing, ionospheric experiments and other research in the field of radio wave propagation.

3.4.1 High Efficient Broad-Band Radiators, Based on Active Antennas with a Plasma Load

Scientific supervisor of the project: Professor G. A. Markov, Chair of the Department of Electrodynamics at the Nizhny Novgorod State University and Dean of the Radiophysics Faculty.

The possibility of using plasma objects produced by the antenna field in a rare gas is a very interesting direction for investigations in the field of a turning vibrator antenna for communication systems at mobil carriers (air crafts, satellites, ships) [176-177]. Plasma inhomogeneities may be localized as a plasma load at the vibrator end. Such inhomogeneities may be formed near both the antenna when completely immersed in the rare gas (for example, ionosphere condition) and near the antenna having a vacuum tube only at the end.

In the process of forming a plasma load, the near field of the antenna changes and leads to the redistribution of the radiating currents and to the modification of an antenna input impedance. As for the plasma load, which has a sensitive dependence on the input power, signal frequency, gas pressure, amplitude and direction of the magnetic field supplied to the plasma, the antenna characteristics may be controlled operatively, and the interval of the variation of the antenna parameters may be rather broad. Therefore, it is possible to obtain a high level of radiating power in a wide frequency band and to control the spectrum of the radiation and the antenna radiation pattern. Unlike the known mechanical methods of matching the antenna with the use of complicated and slowly turning matching devices, the proposed method provides for varying the radiator parameters by means of the control signals. During the investigation, the group had considerable

theoretical and experimental results in the field concerned, and hopes to perform a detailed investigation of antennas with plasma elements, as well as to develop the concrete methods for an operative control of their efficiency and electrodynamic parameters. The group proposes developing the laboratory model of a broad-band vibrator antenna with a plasma load. They expect that a plasma load forming near the antenna field will allow matching the antenna with the source in a frequency range $\Delta f > f_0$ and increasing the radiation power more than twice, as compared with the $\lambda/2$ - vibrator under the given E/M field.

3.4.2 Electromagnetic (E/M) Wave Diffraction on Large Scale disturbances in the plane waveguide

Principal Investigators: Professor Vladimir Dokuchaev, Chair, Department of Radio Wave Propagation, and Dr. Vladimir Yashnov, University of Nizhny Novgorod.

Models of plane waveguides are widely used in hydroacoustics, seismology, and especially in the theory of SLW (super long wave) propagation near the Earth's surface [178, 179]. Recently a nonuniform waveguide with regular inhomogeneities has attracted much attention. This work considers the excitation of E/M waves by electric and magnetic dipoles in a plane waveguide which contains large scale irregularities in the form of a dielectric or metallic cylinder. Algorithms and software are worked out to calculate E/M fields under this conditions. Results of this work could be used to study the impact of meteoric traces, the arc of polar airglow and LF radiowave propagation in the waveguide Earth-ionosphere.

Turbulent Diffusion of Passive Contaminants

This work suggest a new method of theoretical analysis of the effect of both molecular and turbulent diffusion on the concentration of passive contaminants: aero- and hydrosoles, hydrometeors, etc. This

new approach is based on the method of dispersive ratios, used previously in the theory of wavelike processes [180].

The authors have obtained a new dispersive equation for average contaminant concentration. This equation explores the evolution of the concentration of contaminant clouds after its outburst from the factory chimneys as well as during decay of meteoritic material after its combustion in the atmosphere.

3.4.3 Antennas in Ionospheric Plasma

Principal Investigators: Professor Yu. Chugunov and Dr. A. Kostrov, Department of Plasma Physics and High Power Electronics, Institute of Applied Physics, Nizhny Novgorod.
Number of participanats: 5.

GOAL:
Theoretical study and laboratory modelling of electrodynamic processes of nearby satellite-borne antennas in space plasma [181, 182].

Project description:
1. Calculation of antenna impedance in ionospheric plasma, laboratory study of antenna impedance and near field in magnetoactive plasma.
2. Investigation of whistler radiation efficiency by dipole antenna in the ionosphere, as well as propagation and ducting of excited whistler waves.
3. Theoretical and experimental study of nonlinear effects of nearby satellite-borne antennas, including the influence of thermal and ionization effects on their electrodynamic characteristics.

Project applications:
1. Elaboration of new types of nonlinear adaptive antennas.
2. Refinement of the methods of space plasma diagnostics.

3.4.4 Research of Spatial-Temporal Characteristics of Natural and Artificial Disturbances in the Ionosphere and their Influence on Propagation by Radiophysical Methods on Oblique Radiolines

Principal Investigators: Professor O. Troshichev, Dr. N. Blagoveshchenskaya.
The Arctic and Antarctic Research Institute of the Department of Geophysics.

GOAL: Study of irregular structure and wavelike processes in the ionosphere caused by different natural and artificial disturbances.

The Project is expected:

1. to study of irregular structure and dynamic processes in the auroral and polar cap ionosphere related to magnetosphere processes for various conditions of solar-geophysical activity.
2. to study of artificial plasma irregularities created by antropogen influence on the ionosphere.
3. to analyze the main regularities and discovery of signatures of natural and artificial disturbance in the ionosphere.
4. to study influence of different ionospheric disturbances on HF propagation.
5. to design software and hardware for automatic processing of experimental data.

Method of observations:
Doppler measurements of SW radiosignals from a network of an 8-channel Doppler receiver device with digital registration and automatic processing of radiosignals simultaneously from eight radiolines. (A specific point may be used).
Doppler measurements can be suppoted by a network of oblique ionosphere sounders and other geophysical observations in Russia.

Additional information:
The Department of Geophysics in AARI has a great deal of experience in the organization and realization of geophysical apparatus for Doppler measurements. Software developed in the department has been used in studies carried out in the framework of "CRRES" experiments in 1990-1991.
The specialists of the department can participate in international cooperation in the following directions:

1. planning joint radio and geophysical research programs in the high-latitude arctic region;
2. realizating a joint program in the Arctic while providing the observational staff with qualified specialists;
3. designing adjusted models of various geophysical phenomena and processes including algorithms and methods;
4. creating software to process geophysical information;
5. developing hardware and software for Doppler measurements for prompt monitoring of the state of the polar ionosphere;
6. developing software for real-time processing of geophysical data from various instruments and facilities.

3.4.5 Millimeter Wave Radiometer and Radar Remote Sensing of the Environment

Principal Investigator: Dr. Fedoseev Lev Ivanovich, Institute of Apllied Physics, Russian Academy of Sciences.
Research group: Eight researchers (four experienced in airborne investigations).

Special equipment:
1. radiometers (wavelength 0.87; 1.3; 2.2; 3.3 mm);
2. 2 - channel airborne radiometric sensor (2-3 mm);
3. multichannel 2 and 3 mm spectrometers for ozone monitoring (Arctic mission, 1988-1989, Antarctic mission, 1989-1990);
4. pulse radar (3 mm);

5. airborne scatterometers (2-8 mm).

1. Radiometry of Terrain and Troposphere

1.1 Development of technique for predicting of sky brightness, temperature and atmospheric transparency and radiometric contrast and limitation efficiency of radiometric systems in different climatic zones.
1.2 Development of a technique to increase the stability of radiometric images for navigation and mapping applications.
1.3 Investigation of fluctuation of apparent position of sources located outside of atmosphere.
1.4 Design and manufacturing equipment for remote sensing of smoky, dusty terrain (fires, volcano eruptions, sand storms...)

2. Development of Technique and Instrumentation for Middle Atmosphere Remote Sensing

2.1 Techniques for profile determination of temperature and minor constituents in an altitude range of 20-80 km.
2.2 Manufacturing and testing equipment for observation of a few telluric spectral lines simultaneously (ground based and airborne variants).

3. Radar Remote Sensing of Atmosphere and Terrain

3.1 Active sounding of atmospheric formations by high power 3 mm radar.
3.2 Detection and monitoring of oil slicks by radiometers and scatterometer.
3.3 Radar determination of oceanographic parameters.
3.4 Radar mapping.

The results obtained are presented in [183-186].

3.4.6 A New Method for the Determination of Characteristics of Moving Objects Via Their Electromagnetic Emission

An advanced method is proposed which makes it possible to determine some characteristics of moving objects (such as the density distribution of emission sources, the sources pattern, etc.), proceeding from values of its wave field measured at a few points during a limited time. The basis of this method is the new algorithm used for data analysis based on new mathematical methods and has wider application fields in comparison with the ones usually used. In particular, the method can be applied to investigate the objects moving in various natural media (ionosphere, atmosphere, etc.) [187].

Some possible applications of the method are:

1. Investigating static antennas and radiation sources as well as those located on moving objects;
2. Investigating the distribution of space sources in the ionospheric plasma.

Advantages of the method.

Compared to more familiar methods, this method has the following advantages for solving the problem mentioned above: it

1. completely takes into account the influence of the motion of explored objects and gnerally, produces the correct results for any possible motion velocity;
2. eliminates the need for higher quality and more numerous receiver sets than usual and can be realized using the standard receivers and data registration systems;
3. ensures essentially higher resolution, so that details of the emission sources can be made out which are smaller than the wave length.

Authors of proposal:

Dr. Michail Antonets, Department of Mathematical Physics and Computational Mathematics, Radiophysical Research Institute;
Dr. Valery Ugrinovsky, Department of Mathematical Physics and Computational Mathematics, Radiophysical Research Institute.

3.4.7 A Portable Radar for Blind People

In the Super High Frequency (SHF) technology laboratory at the St. Petersburg Institute for Aviation Instrument Manufacture, a small-sized portable radar has been developed for the rehabilitation of the blind. Using this device a totally blind man can detect, by sonic indications, obstacles such as walls, poles, building corners, steps, holes, etc., windows and doors, as well as still and moving vehicles, and can estimate approximately their distance by sound tone. The SHF radiation level complies with safety requirements. The radar prototype was tested by blind people who praised it highly and confirmed that this device is convenient and reliable.

This devidfe has the following characteristics:

1.	Operating frequency, GHz	10
2.	Emitting power, W	less than 10^{-3}
3.	Maximum range, m	10
4.	Operation time of one power cell, h	more than 4
5.	Power supply, V	+9
6.	Dimensions, mm	220 x 60 x 60
7.	Weight, kg	less than 0.5
8.	Temperature, ^{o}C	-20..+40

Large scale production of this device is not possible in Russia due to its high cost and the shortage of SHF components. Our estimations show that in the Western market the price of this device would not exceed US$ 200.

The designers of this device, Dr. L.S. Panich, Dr. S.F. Jakovlev, V. L. Andreev and E.A. Sarkisian, are able to develop it provided that a Western partner can supply the SHF components, prepare the technological documentation, and produce an experimental batch of 10 items within 6 months.

3.4.8 Radio Wave Propagation in Media with Variable Parameters

Principal Investigator: Professor V. I. Krasiuk.

1. Problem: Operational reliability of radio systems for hypersonic aircrafts flying under the influence of strong artificial radiation on the radio communication channel. This problem should be solved for radio communication, remote sensor data transmission, navigation and landing tasks.
2. Analytical methods:
   The Floke theory, the theory of Mathieu equations, the Bogolubov-Mitropolskly disturbance method, the slow fluctuation method, the method of integral equations of the secondary bulk sources, and the Rytov method.
3. Final results:
   a) The laws of influence of media nonlinearities on the functional characteristics of radio lines affected by strong radiation from artificial sources;
   b) The models of radio lines with strong radiation sources and their simulation theory, taking into account spatial-temporal variations in the medium electromagnetic parameters. Amplitude-frequency responses in a wide range from metric to millimetric wavelengths;
   c) Frequency bands of on-board systems for hypersonic aircrafts, and system operation with strong radiation sources;

d) Electrodynamic models for transmitting devices providing radio communication in ionized media with long electron concentration on interleaving intervals.

3.4.9 Development of Manufacturing Principles and Obtaining Initial Data for the Design of a Special Test Bench

The bench is intended for the study of radiotechnic characteristics (overall efficiency, diagram of directivity, reflection coefficient) of on-board antennas with a dielectric thermal screen under high temperature and plasma conditions equal to those in the air. It can be used for the design, adjustment, and on-bench tests of on-board antennas for launching space ships with the simulation of high-temperature heating and plasma which appear when entering the atmosphere.

There are two parts in the test bench: generating the plasma and measuring its chacteristics.

Main characteristics of the bench:

Plasma temperature	2,000 - 20,000^{0}K
Electron concentration	up to 5-10^{16} cm^{-3}
Thermal flow density	0.3-2.5 kW/cm^{2}
Overall efficiency measurement range	0-30 DB
Overall efficiency measurement error	less than 20% (OE 1.0) less than 70% (OE 0.2)
Diagram of directivity measurement range	0-4dB
Diagram of directivity measurement error	+10%
Reflection coefficient measurement range	0.03 - 1.0
Reflection coefficient measurement error	0.1%

The test bench has been operating for more than 10 years at the St. Petersburg Institute for Aviation Instrument Manufacture. Using the test bench, new results on thermal screening (thermal electrical

conductivity, enthalpy) and on-board antenna characteristics have been obtained, as well as a new construction of on-board antenna with characteristics insensitive to aerodynamic heating and plasma.

The research will be conducted in the Laboratory of the St. Petersburg Institute for Aviation Instrument Manufacture, headed by Professor V. F. Michailov, as well as the group including Dr. L. S. Panich, Dr. F. Jakovlev, and V. L. Andreev.

3.4.10 Radio Location Methods of Hazard Level Estimation of Radiation Emissions into the Air from Nuclear Power Plants

During the preliminary experimental research, direct relationships were found between the emission radiation level and the reflected radar signal power, and the weak relationship between the reflected / signal and the polarization of the probe signal. A concurrent finding was the strong relationship between the power of the signal reflected from meteorological formations and the polarization of the probe signal.

The following research is anticipated:

1. the quantitative dependence between the reflected signal power and radioactive emission;
2. development of a coherent cantimetric radar meter;
3. determination of the dependence between a specific effective reflecting surface of ionized air formations (IAF) and their ionizing level;
4. estimation of IAF spatial-temporal characteristics for different types of their formation;
5. estimation of Doppler spectra of signals reflected by IAF and meteorological formations;
6. study of IAF polarization characteristics.

Based on the results of the anticipated research the specifications for the development of radar for to monitor nuclear power plants can be elaborated upon for the measurement of radioactive clouds.

The research is conducted in the laboratory of the St. Petersburg Institute for Aviation Instrument Manufacture, headed by Professor V. F. Michailov, together with Dr. L. S. Panich, Dr. S. F. Jakovlev, V. L. Andreev, with Professor V. A. Poljanskiy, acting as advisor.

CHAPTER 4

The following section of the report describes Russian Institutes in Moscow, Nizhny Novgorod and St. Petersburg and their main research directions in the field of radio wave propagation in the ionosphere. We have attempted to identify the expertise of these research groups and the leading scientists at these institutes.

1. Space Research Institute (IKI), Russian Academy of Sciences

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Telex: 411498 STAR SU
Tel: 0-07-095-333-12-22

The Institute was founded in 1965 on the basis of some departments and laboratories earlier engaged in space exploration at various institutes of the Academy of Science and other agencies. It is the leading organization of the Academy of Sciences and the Intercosmos Council in the field of investigations of outer space, the solar system planets and other objects of the Universe.

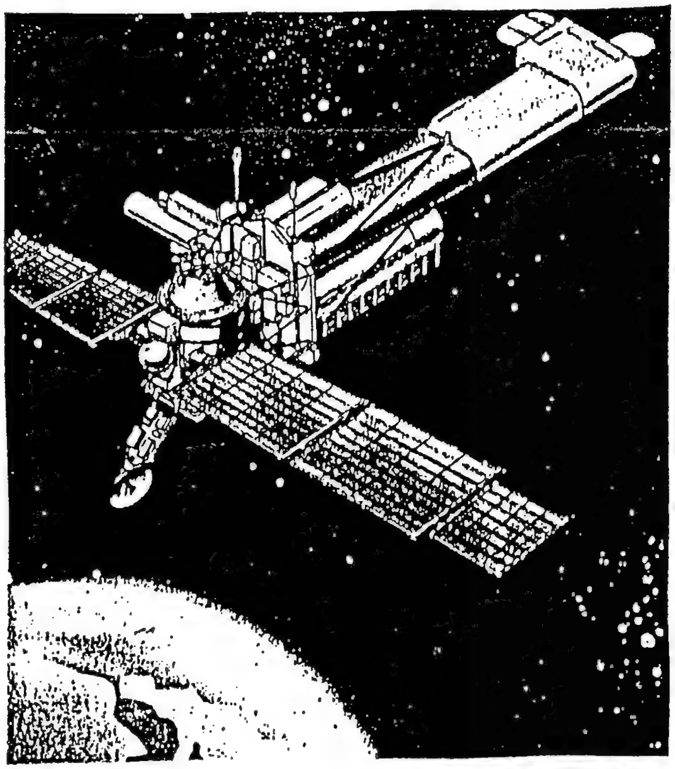
The Space Research Institute prepares and substantiates space research programs, designs, tests and uses scientific instrumentation for such research and ensures international cooperation in the field of space research.

The Institute's structure is determined by the main tasks of its scientific and techical activity. The institute had scientific departments and laboratories studying various aspects of cosmophysics: space plasma, planets, experimental and theoretical astrophysics, space materials technology,

optical and physical studies, as well as departments of scientific and technical reliability of experiments on unmanned and manned space vehicles. The institute possesses a powerful computer basis for processing scientific information. In addition, it has some technical departments and services that include experimental production, design, technical departments, a control-testing station, a department of scientific and technical information and the patent-licencing department.

The Special Design Office in the city of Frunze, has become a powerful design organization with its own experimental production, and a terminal station in the Deep Space Communications Centre in Yevpatoria which processes and transmits scientific information. This office is subordinate to the Space Research Institute, which has its own sections on cosmodromes. The staff takes part in organizing and implementing the final testing of scientific instruments before the launch of spacecraft.

In the town of Tarussa in the Kaluga Region, a new pilot production plant for scientific instrumentation of the Space Research Institute has been set up on an area of 20,000 square metres. For about ten years the Institute was headed by its first director, Academician Georgy Petrov. From 1973 to 1988, this post was held by Academician Roald Sagdeyev. In 1988, A.A. Galeyev, a Corresponding Member of the USSR Academy of Sciences, was elected director of the Institute. About 50 Doctors of Sciences and over 170 Candidates of Sciences work at the Institute.



Spektr-Roentgen-Gamma
Spacecraft

The Institute's staff has participated vigorously in Soviet space programs sush as the Cosmos, Prognoz, Mars, Venera and Luna spacecraft series. Other projects were the Soyuz manned space ships, Salyut space stations and projects carried out within the framework of international cooperation. They included the Soyus-Apollo-test project, the ARAKS project, and the Signe, Raduga, Intercosmos, Vega and Phobos projects, for which time research teams are organized. When conducting manned space flights, the Institute is in charge of the methodological and technical training of cosmonauts who take part in conducting experiments for the Academy of Sciences.

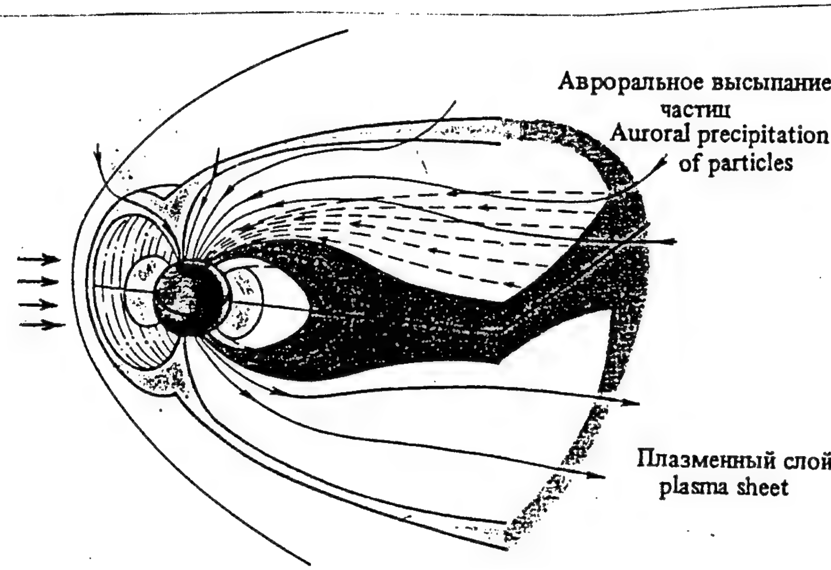
There are three main directions in which theoretical and experimental investigations are performed at the Institute: 1) Plasma Physics, 2) Planetary Physics, 3) Astrophysical Research. Since the end of the '60s a trend had been forming in the development of space research which attempts to apply the new space technologies to study the state of the natural environment - namely ecology.

Plasma physics is one of the main lines of investigation at the Institute. All the stars, including the Sun, the interstellar and

interplanetary media, planetary upper atmospheres (ionosphere) - roughly 99% of matter in the Galaxy is in the plasma state.

Investigation of the plasma in the near-Earth space is reduced mostly to the study of specific individual physical phenomena for complex and interlinked systems such as the solar wind - magnetosphere - ionosphere system. Due to the thermal expansion of the hot plasma of the solar corona, the planets of the solar system are immersed into the supersonic flux of the solar plasma - the solar wind, which was discovered in 1959 by Lunniks. While overcoming solar attraction, the particles of this wind, pushed by a hotter gas, move from the Sun with a constantly increasing velocity.

When the solar wind reaches the magnetic field of our planet, it localizes in the limited comet-like cavity - the magnetosphere. On the side facing the Sun, the boundary of the magnetosphere - the magnetopause - is about 70,000 km away from the Earth's centre. In the opposite direction, the magnetosphere stretches for many millions of kilometers, forming the Earth's magnetic tail. The magnetosphere absorbs only a small portion of the energy of the solar wind flow. Nevertheless, even this energy can cause numerous physical phenomena in near-Earth space, including bright airglows, known as auroral displays.



Experimental studies of the magnetosphere have shown that from the electrodynamic point of view, it must be considered as a single ionospheric magnetospheric system. Various parts of the magnetosphere are electrodynamically connected by currents along the lines of the force of the magnetic field (field-aligned). The strongest field-aligned currents are observed in auroral lines of force (in the zone of aurorae). These currents link the regions of the daytime magnetosphere and the magnetospheric tail (i.e. space regions where the main dynamic processes occur) with the ionosphere.

In studying the physics of the magnetosphere, increasing attention is given to the active diagnostics method, i.e., the injection of the plasma into the magnetosphere, in order to investigate plasma and electromagnetic waves when they are directly generated in the collisionless plasma of the ionosphere and the magnetosphere.

The APEX project is aimed at the controlled study of the electrodynamic links between the auroral ionosphere and the magnetosphere. The project is based on satellite plasma experiments on the injection of electron beams or plasmoids into the magnetosphere with the simultaneous recording of phenomena generated by the injection of the beam, the interaction of the beam with the background environment and the propagation in plasma. The leading organization in the preparation and implementation of the project is the Institute of Terrestrial Magnetism, the Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences (IZMIRAN). The staff of the Space Research Institute participates in the project.

Active experiments of the APEX project are staged with the use of a main satellite and a sub satellite at altitudes of up to 3,500 km. It is of principal importance for the APEX project to provide the synchronous measurements of the basic physical parameters of the environment, the beam and generated fields from the two spacecrafts.

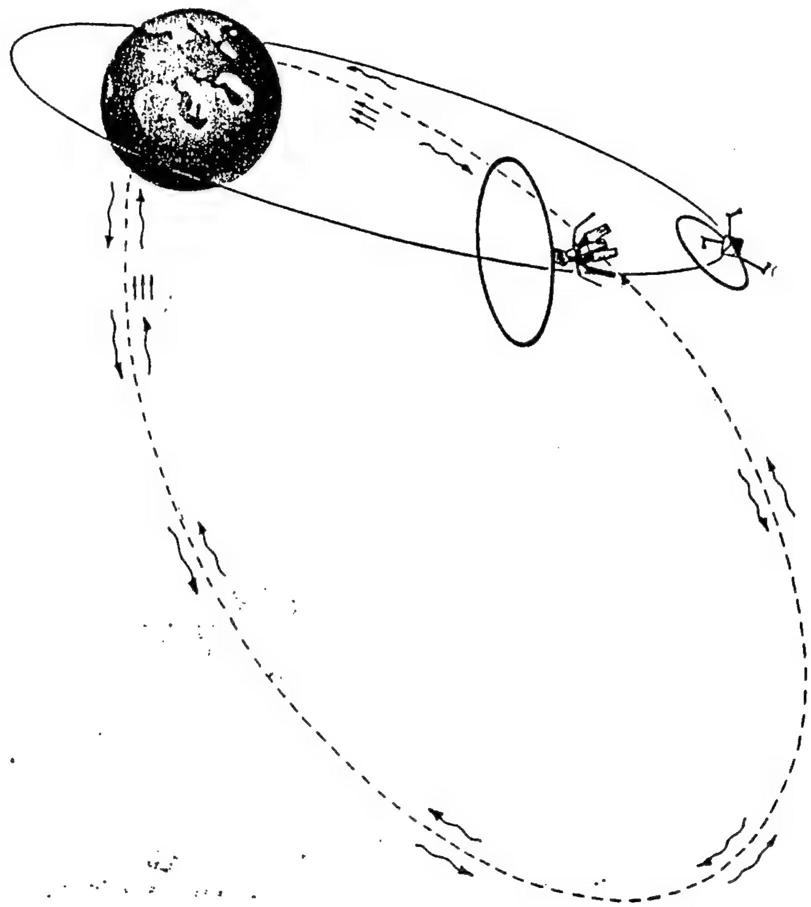


Схема экспериментов проекта «Активный».

Scheme of the experiments of the Activnyí project

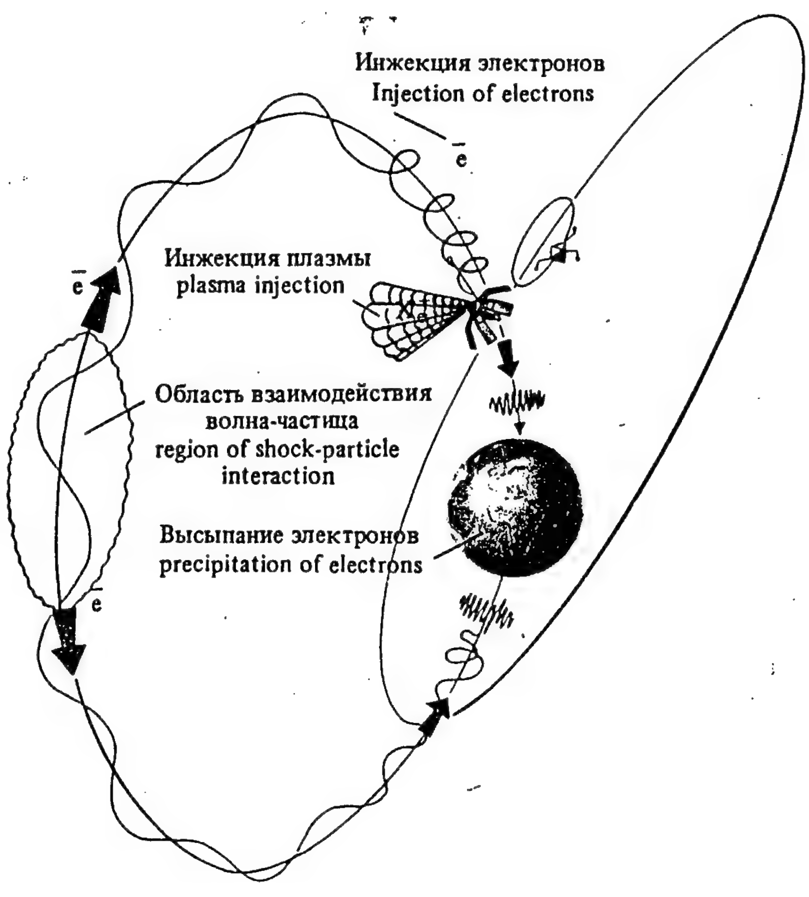


Схема экспериментов проекта АПЭКС

Scheme of the experiments of the APEX project

Simultaneous measurements are performed at different mutual distances (from 0.01 to 1,000-2,000 km) and in different zones of the magnetosphere and ionosphere. Future plans include conducting similiar active experiments with the injection of electron beams and plasmoids at distances of several Earth radii. These experiments will make it possible to directly simulate and diagnose magnetospheric processes to determine the course of various auroral phenomena. Accordingly, the international comprehensive Apogee project, based on the APEX-2 and the Impact project 5, is scheduled for the near future.

In the Aktivny project, electromagnetic energy of very low frequency (VLF) radio range will become a means for exerting influence on the environment. This energy is emitted by the on-board satellite transmitter with the aid of a large antenna unfolded in outer space. The aim of the project is to conduct comprehensive studies of the propagation of VLF electromagnetic waves in the Earth's magnetosphere and investigate their interaction with energetic charged particles of the radiation belts.

The Aktivny is the first space experiment in which the controlled sub-satellite was used for studying the spatial structure of physical phenomena accompanying the injection of powerful VLF radiation into the magnetosphere. The sub-satellite is a specific probe which is slowly separated from the main vehicle. Several institutes of the USSR Academy of Sciences are responsible for much of this program. The Space Research Institute will help these Institutes in developing and testing the scientific instruments.

Two departments at the Institute are specifically connected with ionospheric research: the Department of Space Plasma Physics, headed by Dr. Zelenyi, and the Department of Applied Geophysics, headed by Professor Moiseev.

The main directions of inospheric research conducted in the first department are:

1) VLF propagation in the Earth-ionopshere waveguide;
2) VLF propagation in the Earth's magnetosphere;
3) Stimulation by VLF radiation precipitation of high energetic particles;
4) Stimulation of geomagnetic oscillations by the signals of LF transmitters;
5) Measurements of airglow in the night sky to diagnose the glow of chemical processes.

The leading scientist (involved in ionospheric research) in the Department of Space Plasma Physics is Professor Mikhail Mogilevsky.

His research includes:

1. a theory of power-line harmonic radiation (PLHR) to explain the weekly variation of ELF data observed by a low-altitude satellite [188];
2. observations of VLF emissions in the ionosphere and magnetosphere associated with earthquakes [189];
3. Electric-field measurements in comet P/Halley's environment [190];
4. parametric excitation of ELF waves and the acceleration of ion's by the injection power of VLF waves into the ionosphere [191];
5. precipitation of energetic trapped particles in the magnetosphere over the epicentre of the approaching earthquake.

The main direction of research carried out by Moiseev's group (Department of Applied Geophysics) is the interaction of wave beams with plasma (see part 3.2.8 of present report).

The leading scientist in this group is Professor Nikolai Erokhin. Professor Erokhin is the author of more than 50 publications in Russian and Western publicatons and books (for example, [140-142, 145, 146]. The main direction of his research has already been presented in 3.2.8 of the present report.

2. Institute of Physics of the Earth (IFZ) Russian Academy of Sciences

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Academician Vladimir Strakhov is the Director of the Institute.

In 1928 the Seismological Institute was established by the Soviet Academy of Sciences. In 1956 the IFZ was created and modeled on the Seismological Institute. Its main directions included the origin and evolution of the earth, its internal structure, seismological processes, terrestrial magnetism, gravitation and electro- magnetic (W/M) fields, physics of explosion, as well as geophysical methods of useful fossil exploration and the design of geophysical equipment. Recently, the earthquake forecasts and computational geophysics have gained prominence. The major advance was the elucidation of the main features of the magnetosphere by the on-ground measurements.

Research of the ionosphere is connected to the development of earthquake forecasting. The prediction method is based on the characteristics of super long waves (SLW) propagation in the Earth-ionosphere waveguide [see 3.3.11]. Studies include Ionospheric sources as related to seismic activity.

This research is carried out at the Seismo-Electric Department, headed by Professor Mikhail Gokhberg. The research group includes the leading scientists: Academician Strakhov, Professor Gokhberg, and Professor Molchanov. For more details of this research, see part 3.3.11 of the present report.

3. Moscow Institue of Physics and Technology (MFTI)

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Tel: 0-07-095-408-63-36

Rector - Professor Nikolai Karlov.

MFTI was created in 1951. It's founders and faculty members included such outstanding scientists as Peotr Kapitsa, Nikolai Semenov, Lev Landau, Sergei Vavilov and others.
MFTI consists of nine faculties: Radiotechnics and Cybernetics, General and Applied Physics, Aerophysics and Space Research, Molecular and Chemical Physics, Physical and Quantum Electronics, Aeromechanics, Applied Mathematics, Energetics and Physical-Chemical Biology.
The teaching staff consists of 1441 members out of which 404 are professors. There are about 5000 (M.Sc.) students and 600 graduate students (Ph.D) in MFTI.

The following research is carried out in the field of radiophysics and electronics:

1. diffraction and radio wave propagation in the atmosphere and ionosphere during generation of energy concentration areas in radio navigation and communication systems;
2. problems of radiolocation, in particular sea surface;
3. interaction of laser radiation with matter. Design of laser systems with subnanosecond impulse radiation as well as design of lasers in ultraviolet range with high average power;
4. research in metal and semiconductor films;
5. peculiarities of acoustics and E/M waves in crystal and magnetic media;
6. development of effective numerical methods and software packages for solutions of multi-dimensional problems in radiophysics;

Ionospheric research is carried out at the Deparatment of Antennas and Propagation, headed by Professor Dmitry Lukin. The strong theoretical group includes the leading scientists Professor Lukin, Dr. Kryukovsky, and Dr. Palkin. They have been developing new methods and computational algorithms for solving problems of radio wave propagation and diffraction in inhomogeneous media (for more details see part 3.2.9), including nonstationary problems of superfocusing signals in the small volumes.

4. Institute of Radioengineering and Electronics, Russian Academy of Sciences

Address: 103907, Moscow, Mokhovaya St., 11
Fax: 0-07-095-203-84-14
Tel: 0-07-095-200-52-58
Telex: 412711 FIRE SU

The director of the Institute is Professor Yury Gulyaev, Presidium member of the Russian Academy of Sciences.

The Institute was founded in 1953. Its previous director was Academician Kotel'nikov, who is famous for his contribution to the theory of information. One of his well known theorems on spectrum of function discretization was named in his honour.

The Institue is presently divided into two parts:
The first branch is situated in the centre of Moscow, and the second in the small city of Fryazino in the Moscow region. About 3000 persons work at the Institute.
Its Moscow branch has about 20 Drs. of Science and 100 Ph.Ds.
The Institute has subdivisions in Saratov and Simbirsk (formerly Ul'yanovsk) on the Volga river.

The main directions in research and development at the Institute are the following:

1. modern radio engineering.
2. electronics and communication, particularly in fields such as space radio engineering;
3. millimetre, submillimetre and optical wave bands;
4. remote radiophysical sensing of environment (for example, measurements of humidity by radiation of the earth);
5. high-sensitive detectors of E/M radiation;
6. acousto-electronics devices (for example, dispersive delay lines on surface waves of acoustic thermometers and acoustic thermography of the human body);
7. formation of high power electromagnetic beams;
8. fiber-optics;
9. radar investigations;
10. new principles of information processing;
11. superconductivity, etc.

Research in the field of radio wave propagation is carried out in the following directions:

1. The dispersion distortions of the broad-band signals and their influence on the distance resolution of radars of VHF-UHF (very/ultra high frequency) bands are investigated when they propagate through the earth's ionosphere. Polarization dispersion is taken into account. (The analytical expressions are deduced for the envelope and the frequency modulation of the impulse).
   Research group: N. Kretov, T. Ryshkina, L. Fedorova.

2. The spectral analysis of the temporal changes of electron concentration in the maximum F2-layer in Moscow's environs is being developed. Data for a thirty year period are being analyzed by new methods developed by the authors.
   Research group: A. Shabelnikov, V. Efremenko.

3. Investigation of combinational interaction of relativistic electron beams with plasma in a flat waveguide is being conducted (A high frequency signal wave is formed by one of the

waveguide modes, while the low frequency pumping field is created by the Lengmuire waves of one of the beams).

Principal Investigator: Dr. Nicolas Romashin.

4. Computer simulation of global processes in the magnetosphere is being carried out. A computer code creating a three-dimensional hybrid model of the interaction of solar wind plasma with the Earth's magnetic field is developed.

   Principal Investigators: Drs A. Korzhenevsky and V. Cherepenin.

5. High-power microwave beams propagating in the lower atmosphere are capable of causing ionization leading to microwave gas breakdowns and the formation of a relatively long-life plasma. Laboratory and computer simulation of these effects is being conducted which indicates the possibility of creating an artificial ionized zone in the earth's atmosphere.

This investigation is carried out by Professor N. Armand's group. The results can be used in developing methods of energy transportation through the atmosphere by the creation of an artificial ionized zone in the astmosphere, as well as in solving ecological problems associated with the ozone layer in the Earth atmosphere.

5. <u>Institute of Terrestrial Magnetism, the Ionosphere and Radio Wave Propagation (IZMIRAN)</u>
<u>Russian Academy of Sciences</u>

Address: 142092, Troitsk, Moscow Region
Tel: 0-07-095-334-01-20, 334-01-22
Telex: 412623 SCSTP SU
Fax: 0-07-095-334-01-24

IZMIRAN is the Academic Institute specializing in research connected directly with the ionosphere. Professor V. Oraevsky is presently the Director of the Institute.

There are five divisions at the Institute. Each one has established departments according to their specialization:

1. Investigation of Interplanetary and Terrestrial Magnetic Fields and Magnetospheric Research.
2. Solar-Terrestrial Physics.
3. Plasma and Space Physics.
4. Ionospheric Investigations.
5. Radiophysical and Radiotechnical Problems.

Ionospheric investigations are carried out in the following directions:

1. Effects of high power radio waves on the ionosphere
   a) Excitation of small-scale irregularities in the resonance region at oblique exposure of the ionosphere to a powerful radio wave.
   b) Modelling of travelling strong plasma temperature and density perturbations induced by intense radio waves from the ionosphere to the magnetosphere.
      Principal investigators: Dr. Victor Vas'kov, Head of the Department, and Dr. Yakov Dimant.
      Research group: Drs.: N. Bud'ko, E. Petykhova, G. Komrakov and N. Ryabova.
   c) Artificial ionospheric radio wave generation by plasma wave scattering on small-scale cavitons.
      Principal investigators: Drs. V. Vas'kov and V. Puchkov.
   d) Effects of powerful oblique radiation on the ionosphere.
      Principal investigator: Dr. Gennady Bochkarev (his proposals are presented in part 3.1.9).
   e) Nonlinear effects of radio wave propagation in plasma, in particular the coupling between short and long waves.

Principal investigator: Professor V. Karpman, Head of the Theoretical Physics Department.

f) Diagnostics of powerful radio wave interaction with the ionosphere by multi-frequency Doppler-sounding techniques.
Principal investigators: Drs. V. Kim and L. Lobachevsky.

2. Ionosphere modelling and forecasting

a) Analytical and experimental models of absorption for various geophysical conditions.
Principal investigator: Dr. Pavel Kishcha (for more details see 3.3.9).

b) Modelling of the equatorial ionospheric F2-region.
Principal investigator: Dr. T. Leshinskaya (3.3.3).

c) Global modelling of the ionospheric E-and F2-layers.
Principal investigator: Dr. T. Soboleva, (3.3.4).

d) Modelling of low-latitute F-scattering.
Principal investigators: Drs. N. Ben'kova and M. Fligel.

e) Electron density model correction by simultaneous data on vertical and oblique sounding.
Principal investigator: Dr. L. Shoya.

f) Model representation and mechanism of global longitudinal effects in the topside ionosphere.
Principal investigator: Dr. M. Deminov.

g) Interlayer E-F valley problem in ionospheric modelling with the vertical-incidence sounding data.
Principal investigator: Dr. T. Gulyaeva.

h) Extended forecast of HF communication possibilities in quiet and disturbed ionospheres of middle and high latitudes.
Principal investigator: Professor Evgeny Mishin, Head of the Department, (3.3.2).

3. Development of the theory of radio wave propagation in the inhomogeneous plasma

a) Method of parabolic equation.

b) Gaussian beams summation methods.

c) Nonlinear effects in wave beam propagation through the ionosphere.

d) ELF radio wave propagation in the Earth-ionosphere waveguide.
Principal investigators: Professor Yu. Cherkashin, Head of the Department of Ionospheric Radio Wave Propagation, and Dr. A. Popov, Head of the Laboratory (see 3.2.11-3.2.14).

e) Nonlinear interaction wave beams with ionospheric plasma.
Principal investigator: Professor V. Karpman, Head of the Department.

f) The problem of the fine structure of the auroral ionosphere during substorms. Plasma-turbulent layer energy transformation in the auroral arcs.
Principal investigator: Professor E. Mishin.

g) Propagation and interaction of VLF waves in the Earth-ionosphere waveguide.
Principal investigator: Dr. N. Borisov.

h) Structured VLF emissions in the outer ionosphere.
Principal investigator: Dr. D. Shklyar.

4. Ionospheric data processing:

a) Diagnostics of travelling ionospheric disturbances (TID) by measurements of radiosignal characteristics.
Principal investigator: Dr. T. Kerblay.
Research group: Drs. V. Ivanov, V. Karvetskiy, Ye. Kovalevskaya and N. Korn'kova.

b) Measurements of the ULF signals at the geo-magnetically conjugated points.
Investigator: Dr. D. Fligel.

c) Analysis of topside sounding data for diagnostics of longitudinal variations of F-layer height and concentration of the position of equatorial anomaly crests and ionospheric parameters over the geomagnetic equator.

Principal investigator: Dr. M. Deminov.

d) Fine-scale inhomogeneities in the ionosphere and properties of ionograms of external sounding.

Principal investigator: Dr. S. Pulinets.

e) Topside ionosphere vertical profiles by satellite measurements.

Principal investigators: Drs. N. Ben'kova and M. Fligel.

6. Moscow State University (MGU) Physics Faculty

Address: 119 899 Moscow, Lenin's Hills
TelexL 41483 MGU SU
Tel: 0-07-095-939-30-46
Fax: 0-07-095-939-01-26
0-07-095-939-11-66

The Physics Faculty at Moscow University is well known because of its high quality both in student education and in research conducted by staff scientists.

Ionospheric investigations are carried out in the following directions:

1. radio wave propagation in a randomly-inhomogeneous medium such as the ionosphere;
2. investigation of a randomly-inhomogeneous ionosphere by stastistical tomography method;
3. development of calculation methods and software for radio wave propagation in magneto-active ionospheric plasma;
4. global monitoring of space-time peculiarities of random ionosphere.

Principal investigators: Professor Victor Gusev, Vyacheslav Kunitsyn and Dr. Sergei Golynski.

7. <u>All Union Research Center of Surfaces and Vacuum (VNITSPV)</u>

Address: 117331, Moscow, Kravchenko St., 8
Tel: 0-07-095-137-61-95, - 138-54-46

This Center is working on a variety of problems in different fields of theoretical and applied physics. The main topics of research are:

1. Theory of gravity and precision space-time measurements within gravitational relativistic models (Prof. V.N. Melnikov).
2. Fundamental physical constants and their stability, measurements of the gravitational constant (Professor V. Melnikov, Dr. N. Kolosnitsyn).
3. Gravitational and gradiometric measurements (Dr. N. Kolosnitsyn).
4. Surface parameter measurements using electromagnetic acoustic waves and Auge spectroscopy (Prof. V. Belyakov).
5. Liquid crystals (Prof. V. Belyakov).
6. High precision measurements and metrological applications based on synchrotron, radiatron and the Mossbauer effect (Professor V. Belyakov).
7. High temperature superconductivity and its metrological applications (Prof. E. Shapoval).

8. Plasma diagnostics (Dr. V. Gavrilenko).
9. Metrological aspects of superconductivity (Dr. E. Shapoval).
10. Multiple scattering, signals in the atmosphere and problems of hermeticity (Dr. M. Kalinin).
11. Laser interferometry system for measurements of linear and angular displacement and vibration parameters. Possibility of measurement of linear diplacement with 1-3 nm.

8. Radio Research Institute (NII Radio)

Adress: Moscow, Kazakova St., 11
Tel: 0-07-095-261-36-94
Fax: 0-07-095-261-00-90

The Head of the Institute is Professor Yuri Zubarev.
The staff at the Institute consists of 1730 members.
There is also a pilot plant attached to the Institute.
The main directions of the scientific and technological projects are the following:

1) Radio - relay communication in the CM and MM range.
2) Satellite communication.
3) Anomalous radio wave propagation in the presence of interference.
4) Mobile communication systems.

The Department headed by Dr. Yuri Chernov is involved in ionospheric research, and the development of the theory of HF radio wave propagation. The researchers are carrying out the adjustment of standard calculation methods in radiocommunication for real-life conditions. For example, they take into account horizontal gradients, as well as spread in the "dead zone", ionospheric irregularities, and other ionospheric peculiarities. They determine optimal power for transmitting antenna, beyond which there is no increase in the power of the receiving signal and are also concerned with the morphology of the F-spread.

9. Institute of Physics of the Atmosphere
Russian Academy of Sciences (IFA)

The Head of the Institue is Academician Golitsyn.
It has a staff of 350, of whom 10 are Doctors of Sciences, and 140 are research workers.

There are three experimental stations attached to the Institute: One is in Zvenigorod in the Moscow region, the second is in Tsymlyansk, Rostov, in the Don region and the third is in the Kislovodsk region in the Caucasus.

The main directions of the research are the following:

1. global modelling of climate (Academician Golitsyn);
2. studies of contamination of the earth's atmosphere with industrial gases and aerosols. Urban contaminations, their trends and dynamics;
3. geophysical hydrodynamics;
4. acoustic, optic and radio wave propagation in the atmosphere in particular, and long range sound propagation (Dr. Kulichkov).

Ionospheric research is focused on:

a) Effects of the ground disturbances on the ionospheric D- and lower E - layers, for example, by using experimental explosions in the range of $10\text{-}10^6$ kg of explosive material. (Middle range rockets can be used as a source of disturbance)s.
b) Ionospheric irregularities.
c) Modelling of ionospheric refraction (Dr. Vorob'ev).

The special laboratory of Dr. Elansky is devoted to the study of the ozone layer.

10. Physics Institute, Russian Academy of Sciences (FIAN)
Moscow, Lenin's Prospect

This is the central institute for theoretical physics in Russia. Scientists of the highest caliber, many of them full members of the Academy of Sciences, are working at the Institute. The head of the Institute is Academician Leonid Keldysh.

Ionospheric studies are conducted in the Theoretical Department of the Institute. The head of the Department, Academician V. Ginsburg, is an outstanding scientist in Plasma Physics and Astrophysics. The work of Academician Alexander Gurevich should be also mentioned for its pioneering contribution to the field of nonlinear effects of high power radio waves on the ionosphere. Acad. Gurevich was involved in several projects on heating the ionosphere by the "Sura" facility (Chapter 3.1.1). He is also Head of a Russian group which is expected to participate in the international "Magnetosphere radar" project.

11. St. Petersburg's Institute for Aviation Instrument Manufacture (LIAP)

Address: 190 000, St. Petersburg, Hertsen St., 67
Tel: 0-07-812-118-42-03

This Institute is primarily a teaching institution although a significant segment of the scientific staff is involved in research.

The main directions are:

1. The investigation of the dynamical and statistical effects in HF ionospheric reflection channel. Prediction of ionospheric disturbances at a system of HF radiopath (Professor Blagoveshchensky, 3.3.5,6);
2. Radio wave propagation (group headed by Sergey Yakovlev) through plasma generated by space vehicles, entering the earth's ionosphere - in particular, distortions at the board antennae. (Recently, this group radio-monitored outbursts from nuclear reactors);
3. radio wave propagation through turbulent plasma and dispersion of radio waves by artificial plasma caused by entering space vehicles (Prof. Glagolevsky);
4. elucidation of frequency "windows" allowing uninterrupted radio communication during re-entry of space vehicles into the earth's ionosphere (Prof. Krasiuk);

5. effect of powerful radiation on lower ionosphere during entrance of large orbital platforms (Prof. Kunts).
6. diagnostics of oil rig fires. Design of robots capable of working in fire plasma (Prof. Krasiuk, Prof. Kunts).
   (Specific projects of this Institute are listed in 3.4.7-3.4.10).

12. St. Petersburg Branch of Steklov Mathematical Institute (LOMI)

Adress: ST. Petersburg, Fontanka St., 27
Tel: 0-07-812-210-49-83

The Head of the Institute is the outstanding mathematician Professor Fadeev. The mathematical aspects of radio wave propagation in the ionospheric plasma are being developed in the laboratory of Professor Babich. Specific projects are listed in 3.2.2-3.2.6.

13. The Arctic and Antarctic Research Institute

Address: 199226, St. Petersburg, Bering St., 38
Tel: 0-07-812-352-11-49

Ionospheric research at this Institute is concentrated in the Geophysical Department under the direction of Prof. Oleg Troshichev.

There are four groups in this department:

1. Physics of the Magnetosphere.
2. Physics of the Ionosphere.
3. Radio wave Propagation.
4. Remote Sensing Facility.

Areas of research:

1. Structure and physical processses in the magnetosphere.
2. Diagnostics of the ionospheric irregularities and disturbances of electric and magnetic fields.
3. Fine structure of the Polar ionosphere and estimation of Polar Cap boundaries.
4. Doppler shift measurements of signals on oblique radio lines.
5. Technical support of Arctic and Antarctic stations and collection of ionospheric data from these stations.

Specific projects in this department are described in chapters 3.3.10 and 3.4.4.

14. University of St. Petersburg Radiophysical Faculty

Address: 7/9 University Enbankment, St. Petersburg
Fax: 0-07-812-428-72-40
Tel: 0-07-218-94-884

The Radiophysical Faculty at St. Petersburg University consists of two parts: the Research Institute of Physics in Petergof, and the Radiophysical Faculty itself in St. Petersburg with a total of 220 staff scientists, 20 professors, and 60 research scientists.

The main directions of research are:

1. statistical theory of high frequency radio wave propagation in the inhomogeneous and anisotropic ionosphere;
2. VLF propagation in the Earth-ionosphere waveguide;
3. theory of thin waveguides;
4. modelling of the lower ionosphere, which takes into account solar and magnetic activity;
5. determination of electron density in the lower ionosphere;
6. solar wind exploration.

The Dean of the Radiophysical Department is Professor Makarov. 3.3.6 and 3.3.7 describe specific research projets carried out by this department.

15. Radiophysical Research Institute (NIRFI)

Address: 603600 Nizhny Novgorod, B. Pecherskaya St. 25/14
Tel: 0-07-8312-36-01-88
Fax: 0-07-8312-36-99-02

Radiophysics in Nizhny Novgorod has a long and distinguished history, beginning in 1923. Current research at NIRFI, IPFAN and University of Nizhny Novgorod is also of the highest caliber. The Head of NIRFI is Dr. Sergey Polyakov. Most of the ionospheric research in NIRFI is connected with the "Sura" heating facility. Specific projects are listed in 3.1.1-3.1.8 and 3.4.6.

16. Institute of Applied Physics (IPFAN) Russian Academy of Sciences

Address: 603600, N. Novgorod, Ulyanov St., 46
Tel: 0-07-8312-35-33-00 Fax: 0-07-8312-36-20-61

The Head of the Institute is Academician Gaponov. A wide variety of theoretical and experimental projects in plasma physics are under investigation in this Institute. Professors Ostrovsky and Rabinovich, and Academicians Gaponov and Talanov are the leaders of their respective departments. Professor Litvak heads the ionospheric research department. Specific projects are listed in 3.2.7, 3.4.3 and 3.4.5.

17. Nizhny Novgorod State University

Address: 603600, N. Novgorod, Gagarin's Prosp., 23
Tel: 0-07-8312-65-60-35
Fax: 0-07-8312-36-99-02
Telex: 224846 UNIGO SU

The Dean of the Radiophysical Faculty is Professor German Markov.

Ionospheric research is conducted in the Department of Electrodynamics by Professor Kondrat'ev; in the Department of Radio Wave Propagation by Professor Dokuchaev; and in the Department of General Physics by Professor Stepanov. For specific projects under Professor Markov see 3.4.1. For research carried out by Professor Kondrat'ev's group, see 3.1.10, and for Prof. Dokuchaev's projects see 3.4.2. Professor Nikolai Stepanov is an international expert in nonstationary problems of radio wave propagation in inhomogeneous dispersive plasma.

N.B.: The authors would like to clarify the classification of scientific degrees in Russia and other countries of the C.I.S.:

1 - Candidate of Sciences.
2 - Doctor of Science.
3 - Professor.
4 - Academician - member of the Academy of Sciences.

ACKNOWLEDGEMENTS

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6	Erokhin Nikolai	Prof.	Dept. of Applied Geophys.	333-22-23 Office Fax: 0-07-095-310-70-23 119-67-07 Home
7	Mogilevsky Mikhail	Prof.	Dept. of Space Plasma Phys.	333-22-23 Office

2. INSTITUTE OF PHYSICS OF THE EARTH (IFZ)
B. Gruzinskaya 10, Moscow, 123810

8	Mikhail Gokhberg	Prof.	Deputy Director Head of Seismo-Electric Dept.	254-61-34 252-07-26 Fax: 0-07-095-2549-088
9	Valentin Ulomov	Prof.	Head of Lab.	254-93-05 Fax: 254-90-88
10	Vladimir Strakhov	Academician	Director	
11	Oleg Molchanov	Prof.		

3. MOSCOW INSTITUTE OF PHYSICS AND TECHNOLOGY (MFTI)
Dolgoprudny, Moscow Region, 141 700

12	Yuri G. Krasnikov	Prof.	Deputy Director	408-63-36 333-21-55
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15	Kryukovsky	Dr.		408-50-66

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11 Mokhovaya St., Moscow, 103907

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5. INSTITUTE OF TERRESTRIAL MAGNETISM, THE IONOSPHERE AND RADIO WAVE PROPAGATION, RUSSIAN ACADEMY OF SCIENCES (IZMIRAN)

142092 Troitsk, Moscow region

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20	**Popov Alexei**	Dr.	Head of Lab. Head of Section of Ionosphere and Radiowave Propagation	3340278 Fax: 0-07-095-3340124
21	**Cherkashin Yury**	Prof.	Head of Dept.	3340278

6. MOSCOW STATE UNIVERSITY (MGU)

Lenin's Hills, Moscow, 119899

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7. ALL-UNION RESEARCH CENTER OF SURFACES AND VACUUM (VNITSPV)

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3	Vitaly Melnikov	Prof.	Head of Division	138-54-46 138-04-28
4	Evgeny Petrosian	Dr.	Chief of Dept.	137-61-95 133-14-77
5	M. Kalinin	Prof.	Chief of Dept.	137-61-95

8. RADIO RESEARCH INSTITUTE (NII Radio)

Kazakova St., 11

27	Zubarev Yuri	Prof.	Director	261 36941
28	Chernov Yuri	Dr.	Head of Dept.	267 41 37 Office 431 16 87 Home
29	Istomina Galina		Head of Security Dept.	267 7255 Fax: 261-00-90

9. INSTITUTE OF PHYSICS OF THE ATMOSPHERE (IFAN)

30	Sokolovsky	Dr.		
31	Vorob'ev	Dr.		
32	Kulichkov	Dr.		

10. FIAN - PHYS. INST.

Moscow, Lenin's Avenu

33	Keldysh Leonid	Prof. Academician	Director	
34	Gurevich Alexander	Academician	Head of Lab.	121 3829 Home

11. ST. PETERSBURG INSTITUTE FOR AVIATION INSTRUMENT MANUFACTURE (LIAP)

67 Hertsen St., Leningrad, 190 000

35	Donat V. Blagoveshensky	Prof.		(812) 118 4203 Office (812) 538 1475 Home
36	Kras'uk Nikolai	Prof.		
37	Glagolevsky Vladimir	Prof.		(812) 588 69 10 Home
38	Yakovlev Sergey	Dr.		
39			Director	

12. ST. PETERSBURG BRANCH OF STEKLOV MATHEMATICAL INSTITUTE (LOMI)

RUSSIAN ACADEMY OF SCIENCES

Fontanka St., 27

44	**Babich Vasily**	Prof.	Head of Dept.	552-07-58 Home 210-49-83 Office
45	**Popov Mikhail**	Prof.		311-32-09
46	**Krauklis Pavel**	Prof.		
47	**Molotkov Lev**	Prof. State prize winner		

13. THE ARCTIC AND ANTARCTIC RESEARCH INSTITUTE (AANII).

38, Bering St., St. Petersburg 199226

40	**Oleg Troshichev**	Dr.	Chief of Geophys. Dept.	352-11-49
41	**Blagoveshenskaya Natalia**	Ph.D.	Chief of Lab.	352 0601 Office 538 1475 Home

14. ST. PETERSBURG UNIVERSITY

7/9, University Embankment

42	**Vladimir Krasil'nikov**	Dr.	Vice-rector for Science	218 94884 Office 257 7677 Home
43	**Makarov Gleb**	Prof.	Head of Radiophys. Dept.	Fax: (812) 42 87240

15. RADIOPHYSICAL RESEARCH INSTITUTE (NIRFI)

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52	Ignat'ev Yury	Dr.		
53	Rapoport O.	Dr.	Head of Dept.	
54	Savely Grach	Dr.	Senior Researcher	36 01 88

16. INSTITUTE OF APPLIED PHYSICS, RUSSIAN ACADEMY OF SCIENCES (IPFAN)

Ulyanov St., 46, Nizhny Novgorod, 603600

55	Alexander Litvak	Prof.	Deputy Director	36-58-10 Office 35-33-00 Home Fax: 36-20-61

17. NIZHNY NOVGOROD STATE UNIVERSITY

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18. INSTITUTE OF APPLIED GEOPHYS. (IPG)

129226 Moscow, Rostokinskaya St., 9

Telex: 411914 ZEMLA SU

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60	Danilov Alexander	Prof.	Chief of Dept.	181-45-11
61	Avdjushin	Prof.	Director	187-81-86

19. RADIOTECHNICAL INSTITUTE

10-12, 8 Marta St. Moscow, 125083

22	Vladimir Romanov	Dr. (tech)	Head of Lab. of Cosmic Radioph.	214-16-52 Office 275-70-85 Home

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